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CINETHEODOLITE EVALUATION PROGRAM: CALIBRATION PROCEDURES

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ABSTRACT. This report describes the cinetheodolite calibration procedures currently in use as a result of the continuing cinetheodolite evaluation program of the Naval Ordnance Test Station.

U.S. NAVAL ORDNANCE TEST STATION
China Lake, California
1 July 1961

U. S. NAVAL ORDNANCE TEST STATION

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FOREWORD

This report, covering the calibration procedures used in the NOTS cinetheodolite evaluation program, is the second edition of NOTS Technical Note 3063-107 of the same title, published in January 1961. No major changes have been made in text or illustrations. It is being issued as a Class 3 NAVWEPS report for the benefit of technical personnel at NOTS and other test ranges who may be involved in measuring and calculating cinetheodolite errors.

Technical notes covering other aspects of the Station's continuing cinetheodolite evaluation program, listed as footnotes in the report, are obtainable from Commander, U. S. Naval Ordnance Test Station, China Lake, California, attention Code 3063.

Development of the calibration procedures described here was accomplished between August 1959 and January 1961, and was financed by overhead funds.

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INTRODUCTION

This report describes current NOTS cinetheodolite calibrations performed in the field with portable equipment.

The report is divided into five sections. Section I briefly describes cinetheodolite errors. Section II treats these errors mathematically. Section III is an outline for setting up the measuring equipment and recording the measurements. Sections IV and V discuss the methods for reducing the measurements to camera constants used in the IBM cinetheodolite solution, and the procedures for calculating these constants with the IBM 7090. Section VI is a general discussion.

In the interest of economy the text has been kept as brief and simple as possible. For more explicit description the reader should consult the other reports which are referred to in footnotes throughout the report.

The appendixes present mathematical derivations pertaining to parts of Section II, and are included for the conveience of the reader. Appendix A lists standards error transformation, Appendix B illustrates lens tube bending due to gravity, Appendix C outlines use of programs 8702 and 8705, Appendix D is a sample calibration performed on cinetheodolite Kth 41 Number 445, which can be used as a guide for handling and reporting calibration data, and Appendix E shows standards error.

Figure 1 is a simplified schematic of a cinetheodolite showing mean orientation of azimuth axis, limits of axis wobble, camera housing, elevation trunnion, etc., but not showing internally-mounted azimuth and elevation dials.

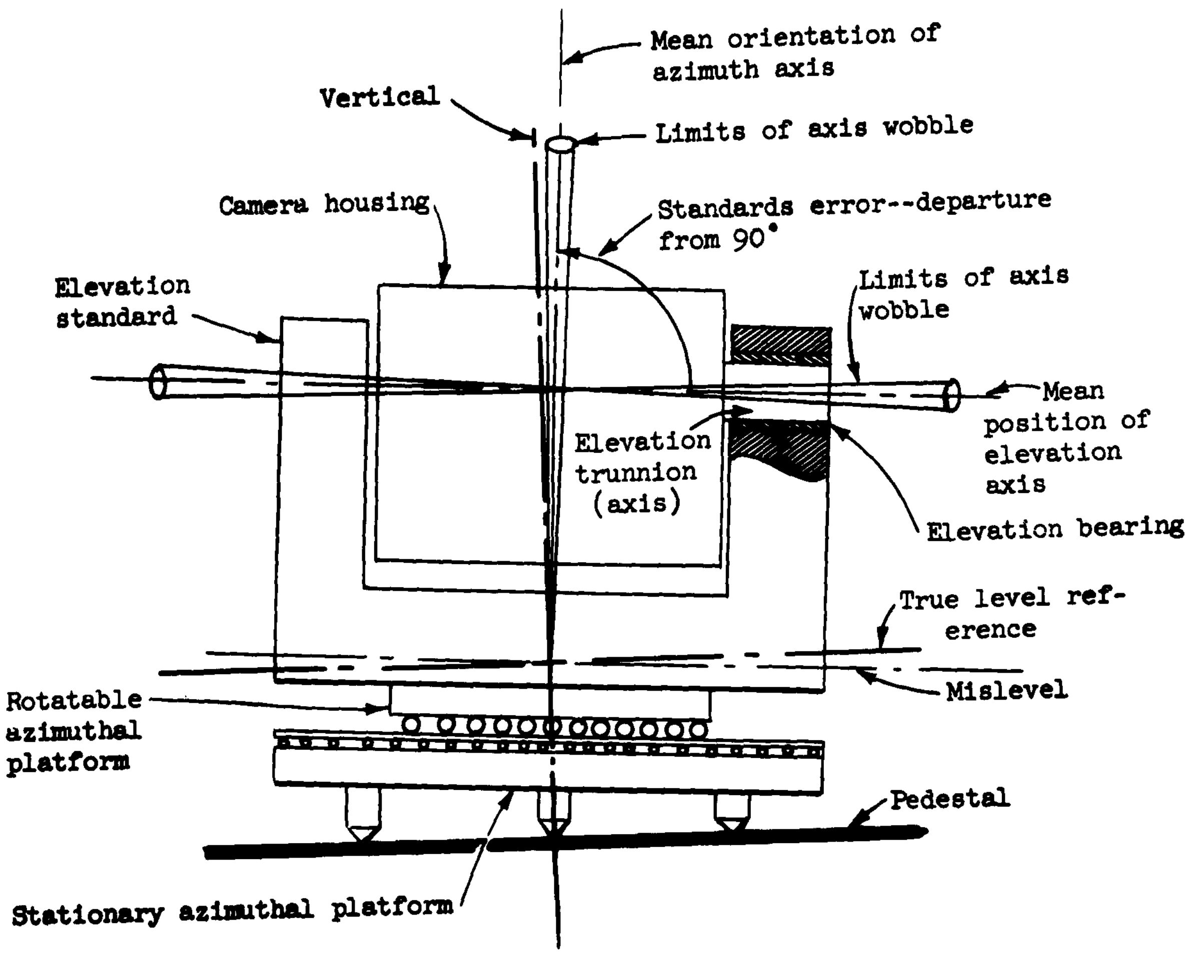


FIG. 1. Principal Features of the Cinetheodolite.

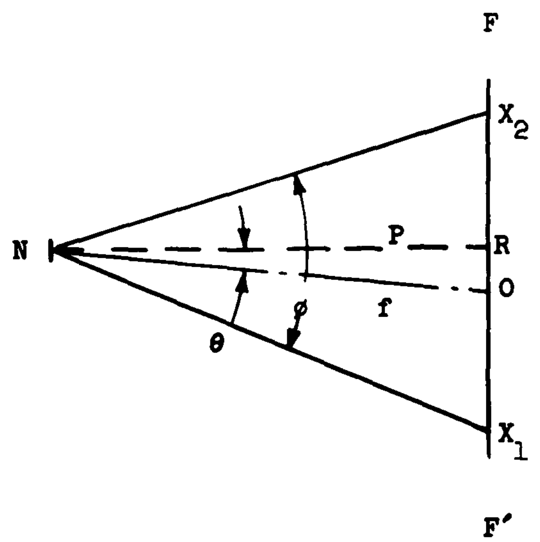
SECTION I

DESCRIPTION OF ERRORS

This section describes cinetheodolite errors which are currently measured. Some of these are biased errors which appear ultimately as constants in the IBM cinetheodolite solution. Others are random errors which indicate the overall accuracy of the cinetheodolite. The errors discussed below are described in greater detail in other Technical Notes, identified in footnotes 1-21. Figure 1 shows schematically the principal features of the two-axis cinetheodolites and some of the errors which are measured.

Principal Distance to the Film Plane[1]

Normal procedure is to focus the cinetheodolite optics in the field. This requires measurement of the principal distance of the film plane in the field. The principal distance is the shortest distance from the principal point of the optics to the film plane, and a line representing this distance is perpendicular to the film plane. Figure 2 is a portrayal of this distance P.



N = Nodal point

FF' = Film plane

ON = Optic axis (primary focus f)

NR = Principal distance P

θ = Nonperpendicularity of film plane to the optic axis

(X_2-X_1) = Linear distance between two images on the film

ϕ = Angular separation of the two images on the film

FIG. 2. Principal Distance.

[1] Marsing, W. D., A Proposed Field Procedure for Determination of Focal Lengths of Askania Lenses, T.N. 3063-1, 23 Mar. 1955, and Mace, R. W., Analysis of the Trigonometric Solution for Focal Length, T.N. 3063-73, Jan 1959, p. ii.

The principal distance is assumed constant for a given focal length setting. Some randomness is attached to p however, due to thermal effects causing f not to be constant. Currently these random effects are not accounted for.

Dial Eccentricity[2]

Ordinarily a dial is mounted to the instrument so that the center of the dial does not coincide exactly with the center of rotation of the instrument axis. As the axis is rotated the center of the dial revolves about the axis of rotation. With respect to a fixed vernier, the dial appears to translate sinusoidally resulting in an error between the actual rotation and the rotation read at the vernier. Figure 3 is a simplified sketch of this phenomenon. If E is in a direction parallel to the vernier, the translation of the dial after a 180° rotation is also parallel to the vernier. The difference of the dial reading from 180° is the eccentricity error e. If differences e_1, e_2, etc. are measured exactly for various rotations, the values of e_1, e_2, etc. vary and will follow a sinusoidal curve. The value e shown in Fig. 3 is the peak-to-peak value of the sinusoidal curve, that is, e is twice the amplitude of the curve. One such curve for one complete rotation is designated a first order harmonic, two curves are designated a second order harmonic, etc.

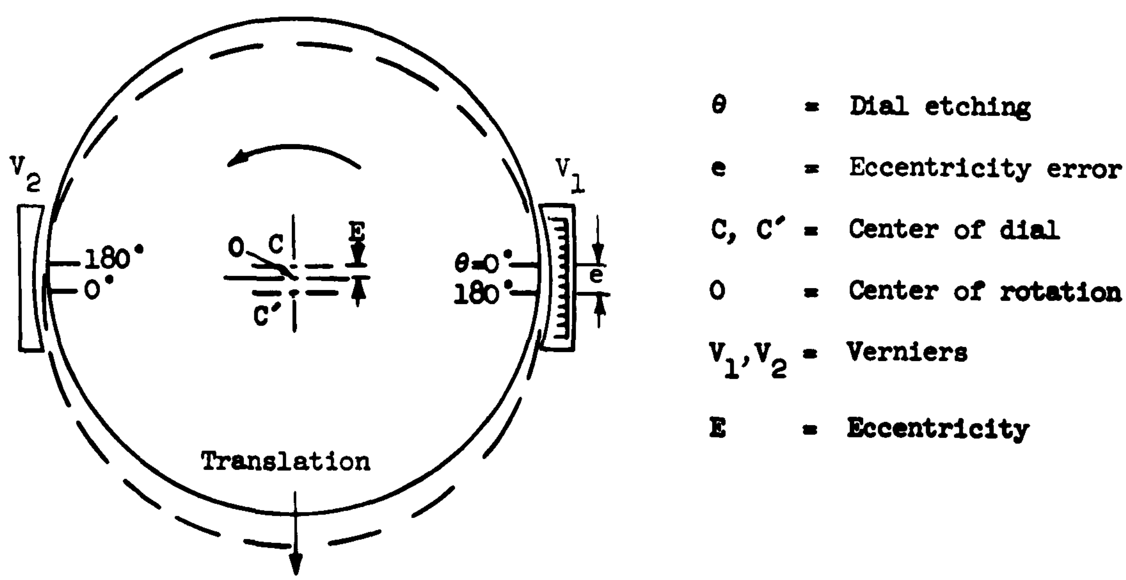


FIG. 3. Dial Eccentricity.

[2] Pratt, A. V. and others, The Askania Evaluation Program, Measurements of the Scale Eccentricity Error, T.N. 3063-17, 9 Sep 1955, p. 1.

The origin of any eccentricity error other than the first, which is due to the eccentricity of the dial, is not always explained. Possible origins are dial etching errors, shaft and bearing runout, eccentricities in the optical trains, and dynamic stresses. Regardless of the origin of the error, all errors of the same order add up algebraically to produce a unique curve of that order. In practice, what we call dial eccentricity is in fact the sum totality of eccentricity-type errors which affect the dial readings.

In some instruments the dial rotates about the axis, in other instruments it rotates about the verniers. The eccentricity errors are identical for the two mechanical models and are measured and calculated by identical methods.

Mislevel, Wobble, and Rollerpath Errors[3]

A rotating axis usually gyrates about some average orientation in space. For example, an azimuth axis which is vertical in space (i.e., its orientation) would, while rotating, tip out of the vertical due to the irregularities of the support bearings and dynamic stresses. These gyrations are termed wobble error. Some of the components of wobble error are biased and some are random. Biased errors are expressed as harmonic errors in the same manner that eccentricity errors are described. Random errors signify probable limits to the accuracy of the instrument.

Wobble error measurements describe only the oscillations of the axis about its mean position. Mislevel specifies the mean orientation of the axis with respect to a given reference. An azimuth axis, for example, is referenced to the vertical, and mislevel specifies the amount and direction in which the axis is tipped out of the vertical. This amounts to not having the support bearing level in space (see Fig. 4). Mislevel $M(\theta_A)$ is expressed by a first order harmonic. The rollerpath errors are then expressed as higher order harmonics, and are the harmonic components of the wobble error measured in one direction.

Mislevel is different each time a cinetheodolite is leveled. For this reason, mislevel cannot be considered a biased error unless it is monitored after each adjustment of the leveling jacks.

Standards Error[4]

Standards error is the angular deviation from 90° of the angle between the azimuth axis and the elevation axis. The error is built into the cinetheodolites and is constant over relatively long periods of time.

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[3] Reisenfeld, W., and others, Azimuth Bearing Wobble Error, T.N. 3063-7, 14 Sep 1954, p. 1; and Ternstrom, A., Various Problems for consideration in Evaluating the M-45 Tracking Mounts, IDP-102, Feb 1956, p. 20.

[4] Pratt, A. V., and others, The Askania Evaluation Program, Measurement of Standards, T.N. 3063-18, Jul 1959, p. ii.

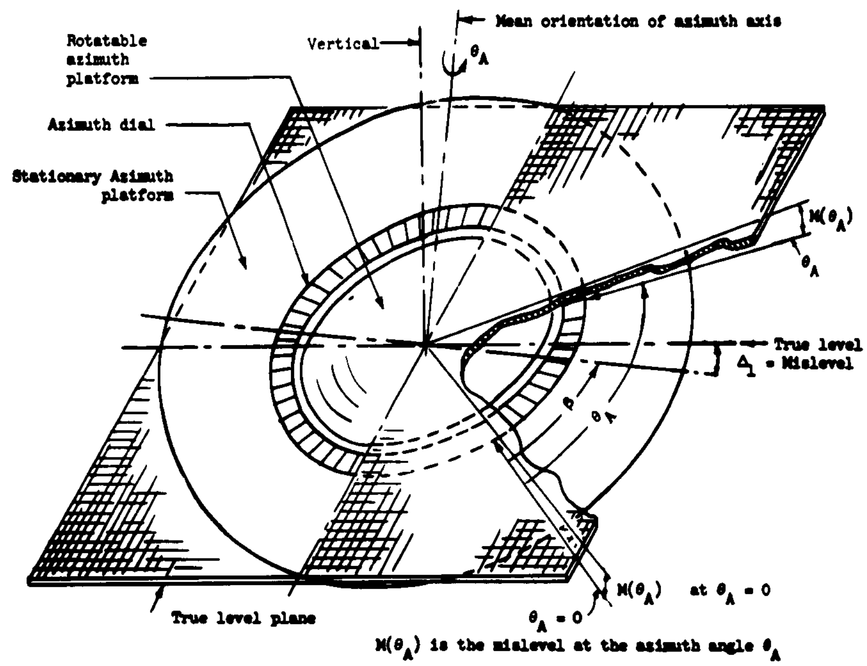

FIG. 4. **Mislevel and the Mean Orientation of the Azimuth Axis.**

The error can be thought of as a fixed mislevel of the elevation axis which causes the instrument to track out of the vertical (see Fig. 1). Superimposed on this fixed mislevel are wobble measurements of the type discussed above.

Lens Tube Sag Due to Gravity[5]

The errors under this nomenclature are of two kinds. The first is actual sag due to gravity of the lens tube under its own weight and the weight of the lenses. The second is bending at the flange and/or the camera housing where the lens tube is attached to the camera. Fortunately both types of bending have the same effect error-wise. Insofar as it is known the bending is linear under the stresses which are applied to the tube.

The effect of this type of bending is to cause translation of the nodal point, causing a corresponding image translation in the film plane, and resulting in an apparent rotation of the instrument about the elevation axis.

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[5] Marsing, W., K-53 Cinetheodolite Lens Bending Measurement and Measurement Procedure, T.N. 3063-15, 7 Jul 1955, and

Marsing, W., A Method of Field Measurement of Lens Tube Bending on Cinetheodolites, T.N. 3063-29, 1 Sep 1955.

SECTION II

MATHEMATICAL CONSIDERATIONS AND EFFECTS OF ERRORS

This section is a brief mathematical description of mechanical errors and their effect upon the useful data obtained from the cinetheodolite's application. All data is ultimately reduced to two angles--azimuth and elevation--defining a ray in space. All measured errors are then expressed so that their effect on these angles is known.

Principal Distance

Two similar methods for calculating principal distance (both using the same data) are available. A comparative study and a derivation of the second method appear in T.N. 3063-73*.

The first method given in T.N. 3063-1* is a trigonometric solution where the relationship

$$P_i = \frac{(X_2 - X_1)_i}{2 \tan \frac{\phi_i}{2}} \quad \text{(see Fig. 2)}$$

is utilized. Several measurements P_i are taken and averaged to give:

$$P = \frac{\sum_i P_i}{n}, \text{ n measurements } P_i .$$

The second method is to apply least squares theory to the above relationship which ultimately reduces to:

$$P = \frac{\sum_i (X_2 - X_1)_i \tan \frac{\phi_i}{2}}{\sum_i \tan^2 \frac{\phi_i}{2}},$$

n measurements $(X_2 - X_1)_i$ and ϕ_i.

Both methods are relatively simple calculations to perform (see Section IV) and the second is not greatly more accurate than the first, since the first method gives percentage accuracy in the neighborhood of 0.2%. The second method gives percentage accuracies of 0.02% or about a factor of ten better.

In the IBM cinetheodolite solution, the principal distance is treated as a focal length measurement. The angular tracking errors are

*See Footnote 1, p. 3.

equivalent to $\tan^{-1}\frac{X}{P}$ and $\tan^{-1}\frac{Y}{P}$ in azimuth and elevation respectively, which are added algebraically to the dial readings A and E, where X and Y are film coordinates to the image.

Dial Eccentricity

Dial eccentricity errors are expressed by a sine-cosine type of relationship of the form:

$$e(\theta) = \Delta_1 \cos(\theta - \beta_1) + \Delta_2 \cos(2\theta - \beta_2) + \ldots + \Delta_j \cos(j\theta - \beta_j),$$

$$= \sum_j \Delta_j \cos(j\theta - \beta_j), \qquad \text{where } \theta = \text{dial angle},$$

and j designates the summation is over the orders which are present, i.e., j is not necessarily continuous through 1, 2, 3, ..., ∞ . The form of the above equation by trigonometric expansion is changed to read

$$e(\theta) = \sum_j (B_j \cos J\theta + C_j \sin J\theta)$$

where

$$\Delta_j = (B_j^2 + C_j^2)^{\frac{1}{2}} \quad \text{and} \quad \beta_j = \tan^{-1}\left(\frac{C_j}{B_j}\right)$$

The B_j and C_j are constants designating the orthogonal components of the sine-cosine function. For the determinates of B_j, and C_j for first and second order harmonics, the reader is referred to T.N. 3063-58[6]. IBM computations (see Section IV) are used to calculate the eccentricity constants.

The eccentricity constants are used to correct the dial readings. For example, the correction to the azimuth dial readings would be

$$e(\theta_A) = \Delta_1 \cos(\theta_A - \beta_1) + \Delta_2 \cos(2\theta_A - \beta_2) + \ldots,$$

where θ_A = azimuth dial reading.

This expression is currently carried out to the third order correction.

Mislevel and Bearing Wobble

These errors have the same form as dial eccentricity errors, that is

$$M(\theta_A) = \sum_j A_j \cos(j\theta_A - \beta_j), \qquad \text{where } \theta_A = \text{azimuth angle}$$

[6] Bondelid, M. A., Coefficients for First and Second Order Harmonic Equations. T.N. 3063-58, Jan 1959.

The corrections these errors make to the elevation and azimuth angles are somewhat more complicated. To completely specify the orientation of the azimuth axis relative to its mean position, components of the deflections of the axis need to be known. The most useful components of wobble error are orthogonal ones measured parallel respectively to the elevation axis and the optic axis. These are called rollerpath errors. The component parallel to the optic axis affects the elevation angle directly. The component parallel to the elevation axis affects the levelness of the elevation axis, and can be thought of as a variation to the standards error.

The wobble errors are made small for the cinetheodolite. Calibrations are currently used, except in special cases[7], to determine if a bearing requires maintenance. It is possible to define an ellipse of concentration[8] (see Fig. 1) which defines a conic of solid angle giving boundaries to the axial wobble. The boundary is determined by statistical methods which will not be given here.

Mislevel is random and can be useful only if the cinetheodolite is calibrated at the time it is used to gather data. This requires automation, a capability the instrument does not currently possess. The calibration data can be used to signify a probable leveling capability during field operations.

Standards Error

The effective mislevel of the elevation axis causes the line of sight to track through a plane which is not vertical in space. Reference to Fig. 5 will facilitate visualization of this error. The description given here is a modified version of the analytical derivation of the standards error correction given in T.N. 303-1.[9]

Figure 5a is drawn to show that, if the cinetheodolite is rotated through the azimuth angle A, then through the elevation angle E about the horizontal (standards error = zero) or about the elevation axis (standards error = s), the optic axis points in different directions for the two cases. Here r represents the optic axis rotated in the vertical J, K plane and r' the optic axis rotated in the nonvertical j, k plane.

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[7]Significant warpage of the camera base produces a higher order harmonic and causes wobble for which a correction should be made.

[8]Bondelid, M. A., Mace, R. W., A Statistic for Determination of Axis Wobble Error in Instrument Mounts, T.N. 3063-85, Aug 1959.

[9]Holloway, W. P., Modifications of the Current Theodolite Least Squares Solution, T.N. 303-1, Nov 1955, pp. 5-7.

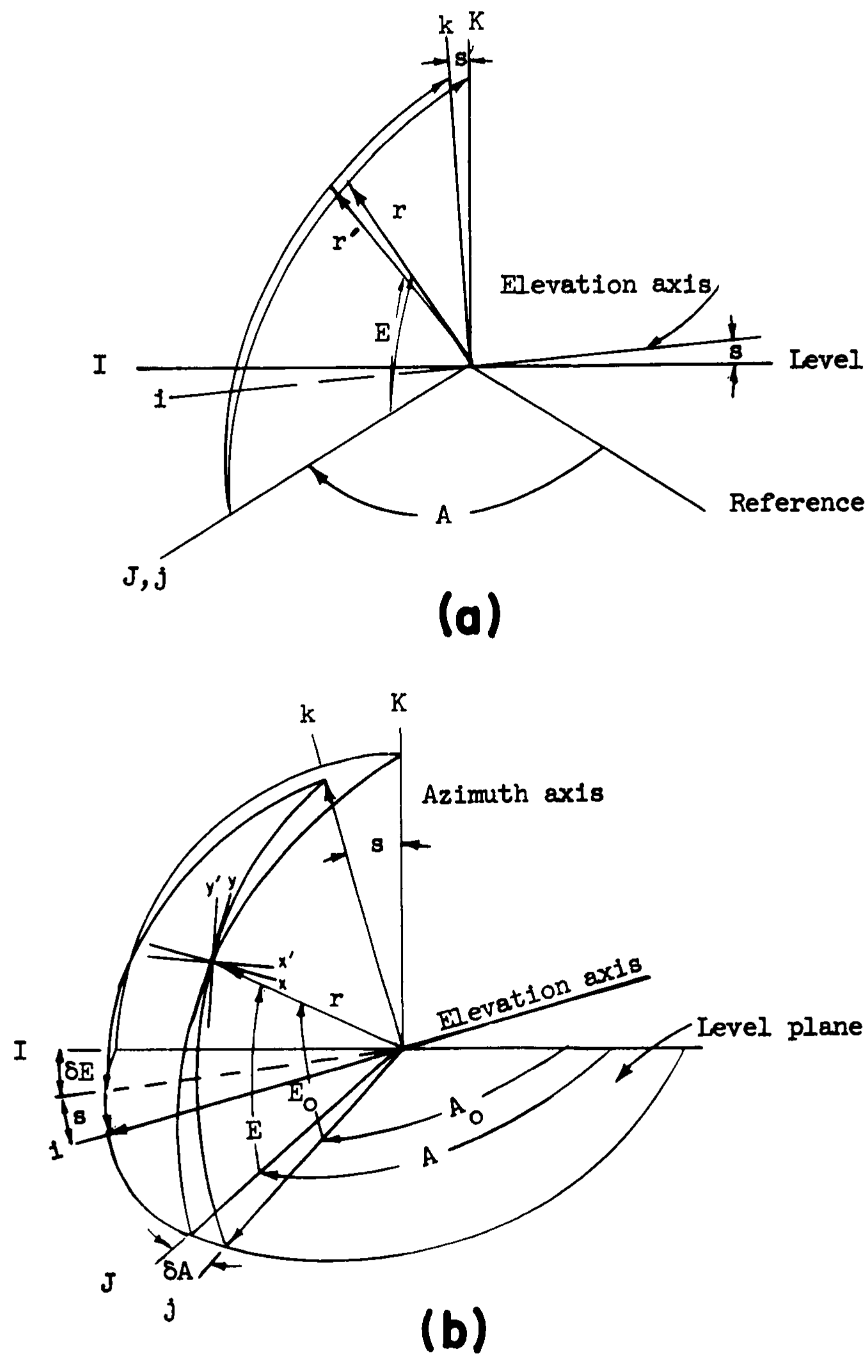

FIG. 5. Standards Error Transformations.

Figure 5b is drawn to indicate what rotations are necessary to compensate for the standards error, i.e., to render r' coincident with r. The camera has to be rotated through δA to A_o in azimuth and δE to E_o in elevation to do this. The angles A_o and E_o are dial readings corrected for eccentricity errors, etc.

Appendix A gives the equations for the transformation to the camera coordinates i, j, k from I, J, K, and values of A and E when A_o, E_o, and s are known.

There are three methods to calibrate for standards error[10]. The method currently in use is given in T.N. 3063-96. Under Section III, Standards Error Measurement, the equations used to calculate the standards error are given. These equations are derived in Appendix E. These calculations yield the result:

$$|S| = |90 \pm s| .$$

The angle S is the angle between the elevation axis in the direction of the tracking optics and the azimuth axis. The angle s is the standards error for which corrections must be made.

Another error caused by the standards error is the rotation of the film plane about r. This is indicated on Fig. 5b by x', y' film coordinates.

Lens Tube Sag Due to Gravity[11]

The lens tube sag is expressed as an angle in degrees of arc. This angle is the effective angle of rotation of the optic axis as the nodal point translates laterally under the bending moments.

Lens bending measurements are used to correct elevation angles in the following manner. Assuming that the bending is linear, the gravitational force produces torques on the lens tube which are proportional to the cosine of the elevation angle (Fig. 6). This correction is subtracted from the elevation dial reading.

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[10] Pratt, and others, T.N. 3063-18, pp. 7-9; and
Mace, R. W., A Method to Measure Bending and Standards Error of an Elevation Axis on Camera Mounts, T.N. 3063-45, pp. 2-10; and
Curry, E., Standards Error Measurement Using Level Vial Technique, T.N. 3063-96.

[11] Mace, R., Cinetheodolite Evaluation Program: An Application for Measurement of Lens Tube Sag Due to Gravity, T.N. 3063-104, Dec 1960.

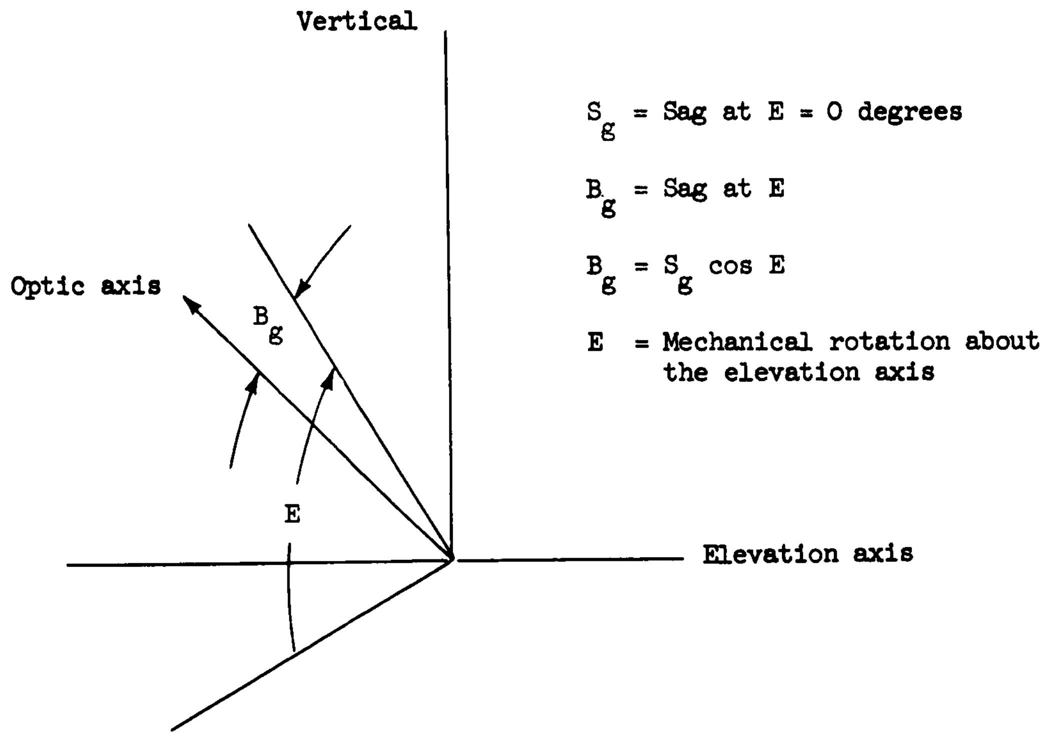

FIG. 6. Correction for Lens Tube Sag.

The sag angle does not affect the cinetheodolite orientation angles if the sag is equal in the forward and dumped position. If the sag is not equal in both positions the effect is to change the value of the orientation angle O_E of the elevation. The correction σ_s is:

$$\sigma_s = \left(\frac{S_D + S_F}{2}\right), \qquad S_D = \text{sag dumped}, \quad S_F = \text{sag forward}$$

See Appendix B for derivations.

The values S_D and S_F are measurable quantities. They are determined by measuring S_F/S_D and $S_F + S_D$ from which S_F and S_D are solved.

SECTION III

CINETHEODOLITE CALIBRATION PROCEDURE

This section is an outline of the procedure for setting up calibration equipment and taking and recording measurements. It is intended primarily as a guide. Each calibration procedure is divided into subsections. The first subsection is a check list of equipment needs. The second and third subsections discuss positioning and alignment procedure. The fourth discusses the taking of measurements.

Each calibration procedure except principal distance is accompanied by a photograph of the equipment. Accompanying the procedures are sample data sheets. The measurements and calculations to determine principal distance are performed by the Data Analysis Branch, Code 3033, and only the picture taking is performed by the Optical Instrumentation Branch, Code 3063. The determination of Mark V dial eccentricities is done by photographing the dials.[12] This film is also measured by Code 3033.

The order of the outline given below does not necessarily dictate the order while calibrating cinetheodolites. The measurement of principal distance should be made any time the optics are focused. It is advantageous to calibrate the dial eccentricities at the same time since they require the same equipment. For the same reason, mislevel should be measured when the azimuth dial eccentricity is being measured and lens tube sag when the elevation dial eccentricity is being measured. This suggests an order of calibration of mislevel, azimuth dial eccentricity, elevation dial eccentricity, and lens tube sag.

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[12] Josephson, J., Least Squares Multiple Order Harmonic Analysis With Mark V Cinetheodolite Dial Eccentricity Calibration Procedure: NOTS IBM Programs 7402 and 7403, T.N. 3063-106, Jan 1961.

Principal Distance

1. Equipment

   A. Fifty-foot roll of Anscochrome film (super Anscochrome for 88-inch Snyder lenses)

   B. Film box

   C. Orientation light

2. Mounting and position of equipment

   A. Put camera in operational condition:
      1. Synchronize the shutter
      2. Check the flash lamps (azimuth dial pictures have to be taken)
      3. Check collimation (very carefully)

   B. Load and identify the film. The identification should give the date, camera number, and lens code.

   C. With the camera ready to take pictures, mount the orientation light on the camera cover if the target is a corner reflector. (For 88-inch Snyder lens use an orientation light at another station as a target.)

3. Alignment of equipment

   A. Point the cinetheodolite at the target and engage the elevation gear.

   B. Adjust the elevation until the target is centered in the tracking scope. If a corner reflector is used, a slight adjustment of the orientation light may be required.

4. Recording measurements

   A. While taking pictures, slowly pan across the target and back. Panning should be through an angle great enough so that the target comes into the field of view on one side of the tracking scope and out the other side. The target should be panned at a constant rate of travel. At least 40 exposures should be made in each direction.

   B. The film is developed by the Photo Lab. After it is returned it is edited prior to forwarding it to Code 3033. There should be a minimum of not less than 40 measurable frames and those images should be distributed evenly across the film plane.

Mislevel and Azimuth Rollerpath Error

1. Equipment
   - A. Autocollimator and transformer
   - B. Autocollimator plate
   - C. Yoke (Instrument support across standards, Fig. 7)
   - D. Farrand vertical leveling (pendulum) mirror
   - E. Tool box
2. Positioning and mounting of the equipment (Fig. 7)*
   - A. Mount the yoke on the camera.
   - B. Mount the autocollimator plate on the yoke such that the center of gravity of the autocollimator will lie over the yoke.
   - C. Mount autocollimator on the autocollimator plate. There are two measurements--one parallel and one perpendicular to the elevation axis.
   - D. Mount the pendulum mirror in front of the autocollimator on the autocollimator plate.
3. Alignment of the equipment
   - A. Level the camera with the camera level bubbles.
   - B. Level the autocollimator with the autocollimator leveling screws.
   - C. Unlock and level the pendulum mirror and adjust with small rotations until the reflected image is read in the autocollimator. Recheck levelness of the mirror.
   - D. Adjust the reflected image slightly off-center vertically with the autocollimator leveling screws.
   - E. Determine zero on the internal azimuth scale and relate to the corresponding reading on the external azimuth scale. The internal scale may be read through the scale reading optics on the camera.
4. Recording measurement (see Sample Data Sheet #1)
   - A. Check all screws and clamps for tightness.
   - B. The camera is rotated in 30-degree increments, the first setting on the external scale being the position of the camera when the internal scale reads zero degrees.

*Figure 7 shows the autocollimator aligned parallel to the elevation axis. To measure the component of wobble error parallel with the optic axis, mount the collimator to face toward the rear.

C. For each setting of the azimuth, read the autocollimator scale.

D. Take three sets of readings over three complete rotations of the camera forward, back, and forward.

E. Record measurements on Calibration Data Sheet #1.

F. Draw in an arrow and rectangle on the picture in the upper right-hand corner of the data sheet to indicate the direction of the autocollimator and the position of the pendulum mirror.

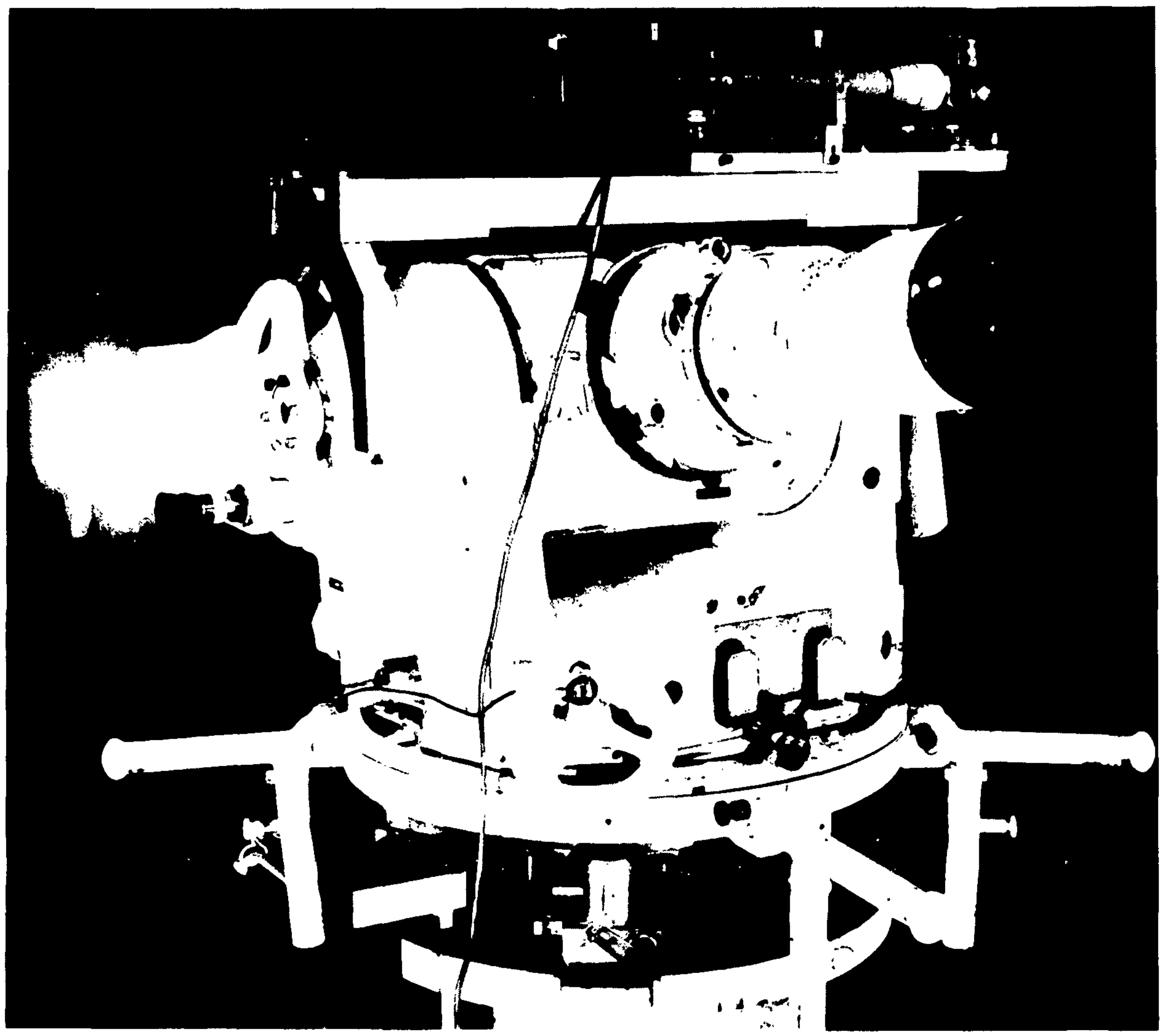
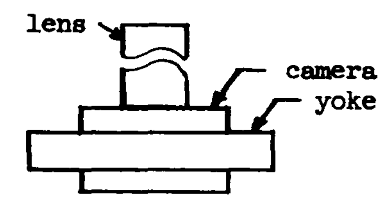


FIG. 7. Equipment Alignment, Azimuth Mislevel, and Rollerpath Error.

AZIMUTH MISLEVEL AND ROLLER PATH - CALIBRATION DATA SHEET No. 1
NAVORD NOTS 4120/5 (9-61)

CAMERA NO.		CALIBRATED AT	EQUIPMENT ALIGNMENT
CAMERA CODE NO.	CAMERA LOC	REMARKS	
DATE			
CREW			



DRAW IN ARROW FOR THE AUTOCOLLIMATOR AND LOCATE THE "FARRAND" MIRROR.

MEASUREMENTS

DEGREES	AZIMUTH DIAL θ_A	AUTOCOLLIMATOR READINGS					
		FORWARD	BACK	FORWARD			AVERAGE
0							
30							
60							
90							
120							
150							
180							
210							
240							
270							
300							
330							
360							

Azimuth Dial Eccentricity

1. Equipment: Mk 2 and Kth 41 type cameras (Mark V dial eccentricities are measured by taking pictures of the dials. See Step 5)
   - A. 30-degree polygon
   - B. Yoke and triangular polygon holder
   - C. Autocollimator, transformer, and autocollimator plate
   - D. Tripod, spider, and Mitchell head
   - E. Cross Test Level
   - F. Microscope and 60mm objective, aperture prism
   - G. Azimuth dial light
   - H. Tool box
2. Mounting and positioning of equipment (Fig. 8)
   - A. Remove azimuth dial flash lamp unit and mount dial illumination lamp.
   - B. Mount the aperture prism and microscope.
   - C. Mount the yoke on camera.
   - D. Mount the polygon holder and polygon on the yoke.
   - E. Mount the autocollimator on the tripod and position so the autocollimator looks at the polygon, with reading scale horizontal.
3. Alignment of the equipment
   - A. Level the camera with the camera leveling vials.
   - B. Level the autocollimator with proper adjustment in height to view the polygon, i.e., the optic axis of the autocollimator should look at any one face of the polygon.
   - C. With the small cross test level laid on top of the polygon, level the polygon by adjusting the leveling screws of the polygon holder.
   - D. Rotate the camera so that zero is read on the internal azimuth dial. If not possible to read, set as close as possible. It may be necessary to read the opposite end of the vernier, i.e., the 359°5 dial mark set at 50 on the vernier.
   - E. With the autocollimator looking approximately at the center of rotation of the polygon, rotate the polygon so that the autocollimator light circle is reflected from a face of the polygon and seen as the observer sights along the side of the autocollimator barrel.

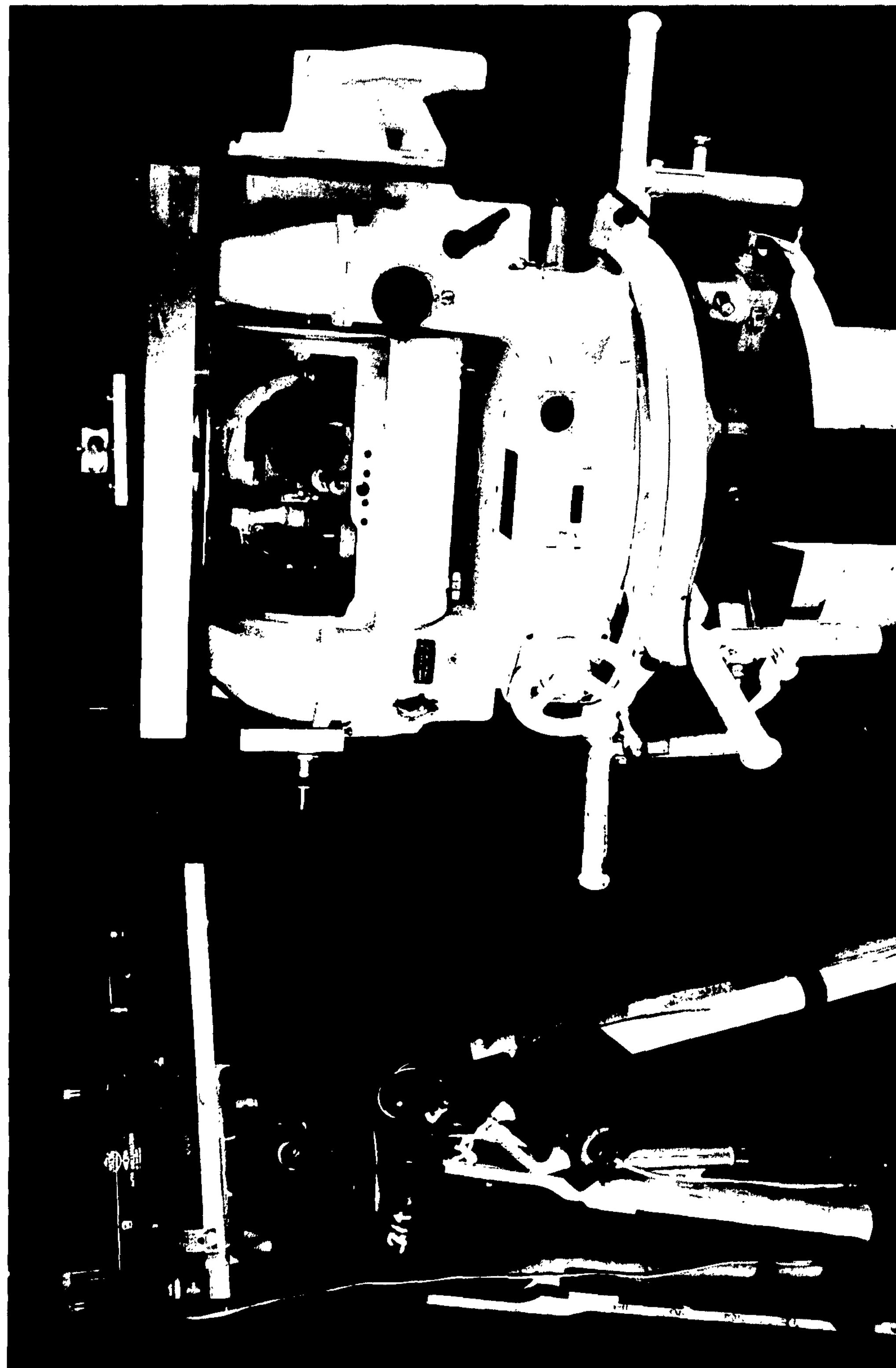


FIG. 8. Equipment Alignment, Azimuth Dial Eccentricity.

F. Adjust the autocollimator height so that the reflected circle appears at the same height and is parallel to the autocollimator. The observer should position his eye to look parallel to the autocollimator.

G. Rotate the polygon to bring the reflected light into the autocollimator field of view. If the light does not pass through the field of view, repeat Step F.

H. When the autocollimator and polygon are adjusted so that the vertical crosshair falls within the reading scale, rotate the camera and note the travel of the horizontal crosshair as the light is reflected from successive faces of the polygon. Reduce this travel to less than half the scale by further leveling of the polygon.

I. Leveling of the polygon using the autocollimator:

1. Rotate the camera and note which faces are associated with the end points of the travel of the horizontal crosshair.

2. With either of these faces towards the autocollimator, adjust the leveling screws of the polygon holder to produce the scale reading midway between the end points.

3. If both end points are not initially visible, rotate the camera to the visible end point, and adjust the level of the polygon so that the image moves in the direction the image would move if the camera were rotated. Repeat 2, 3, and 4 until both end points are visible.

4. To center the total travel of the horizontal crosshair in the field of view, adjust the level of the autocollimator.

5. Repetition of the above steps will bring about any desired levelness of the polygon, excluding camera mislevel.

J. When the polygon has been satisfactorily leveled, set the azimuth dial on the zero reading, rotate the polygon so that the vertical crosshair is readable, and tighten down the polygon.

K. Tighten all holding screws and clamps.

4. Recording measurements (see Sample Data Sheet #2)

A. Record the face numbers of the first and second faces of the polygon and the polygon number on the data sheet.

B. Increments of thirty degrees are set in on the azimuth dial starting at zero. The dial settings are made by reading the internal azimuth dial through the microscope. These settings should be made as close as possible.

AZIMUTH ECCENTRICITY - CALIBRATION DATA SHEET No. 2
LIND NOTS 4120/6 (9-61)

CAMERA NO.		POLYGON NO. 1ST FACE 2ND FACE	NOTE: REPEAT MEASUREMENTS IF CLOSURE OF READINGS DOES NOT OCCUR. CHECK FOR LOOSE CLAMPS. READINGS ACROSS THE PAGE SHOULD BE WITHIN A TEN-SECOND RANGE.
CAMERA CODE	CAMERA LOC	REMARKS	
DATE			
CREW			* POLYGON CORRECTIONS ARE FOUND IN T.N. 3063-102

MEASUREMENTS

DEGREES	AZIMUTH DIAL θ_A	AUTOCOLLIMATOR READINGS FORWARD	BACK	FORWARD			AVERAGE	POLY.* CORR.	CORRECTED READINGS
0									
30									
60									
90									
120									
150									
180									
210									
240									
270									
300									
330									
360									

C. For each azimuth dial setting, the position of the vertical crosshair is read and recorded on Calibration Date Sheet #2.

D. Readings are taken for three complete rotations of the camera forward, back, and forward.

5. Mark V azimuth dial eccentricity calibration.

A. Load the camera with a 50-ft foll of Anscochrome film.

B. Viewing the azimuth dial through the scale optics, set the dial at zero degrees.

C. Rotate the camera in thirty-degree increments read on the internal scale. (Be sure plunger is pulled out after each setting.)

D. For each setting, take a group of pictures in the following manner:

1. Turn on shutter motor switch and allow several flashes of flash lamps to over-expose one frame of the film.

2. Turn off shutter motor switch and turn on camera motor switch.

3. Hand pulse several frames using the single frame push button switch.

4. Switch synch-operate switch to the OFF position and hand pulse one or two frames.

E. Pictures are taken for a complete rotation of the camera.

F. The remaining film is used to take pictures of the elevation dial described under Elevation Dial Eccentricity.

G. The processed film is sent to the Assessment Division; this procedure is described in TN 3063-68.*

---

*Mace, Richard W., Determination of Dial Eccentricity of Mk 5 Cinetheodolites, Tech. Note 3063-68, February 1959.

Elevation Dial Eccentricity

1. Equipment: Mk 2 and Kth 41 cinetheodolites (for calibration of a Mk 5 elevation dial see Step 5).

   A. 15-degree polygon

   B. Polygon holder which bolts on end of elevation axis

   C. Microscope, 60mm objective, aperture prism

   D. Elevation dial light

   E. Autocollimator, transformer, autocollimator plate

   F. Tripod, Mitchell head and spider

   G. Cross test level

   H. Tool box

2. Mounting and positioning equipment (Fig. 9)

   A. Mount the microscope, aperture prism and objective.

   B. Remove from the end of the elevation axis the counter weights and dovetail which hold the tracking optics.

      1. Loosen the six screws in the end of the axis, and the allen screw on the dovetail which is used for adjusting collimation. When the dovetail is loose, pull out.

   C. Remove the elevation dial flash lamp assembly and mount the dial illumination light in such a way that the light will not rub the dial.

   D. Mount the polygon holder on the end of the elevation axis.

   E. Mount the autocollimator on the tripod to look at the polygon, with the reading scale vertical.

3. Alignment of equipment

   A. Level the camera with the camera leveling bubbles.

   B. With the cross test level, level the polygon holder vertically in space.

      1. With the cross test level held to read the vertical level, adjust the polygon holder. Rotate the camera 90 degrees in elevation and repeat the adjustment for this position. Repeat this procedure until the polygon holder has been leveled vertically.

   C. Mount the polygon on the polygon holder.

   D. Set the internal elevation dial on zero degrees. Read the dial through the microscope. (If it is not possible to set the dial on zero when viewing through the microscope, set as close as possible.)

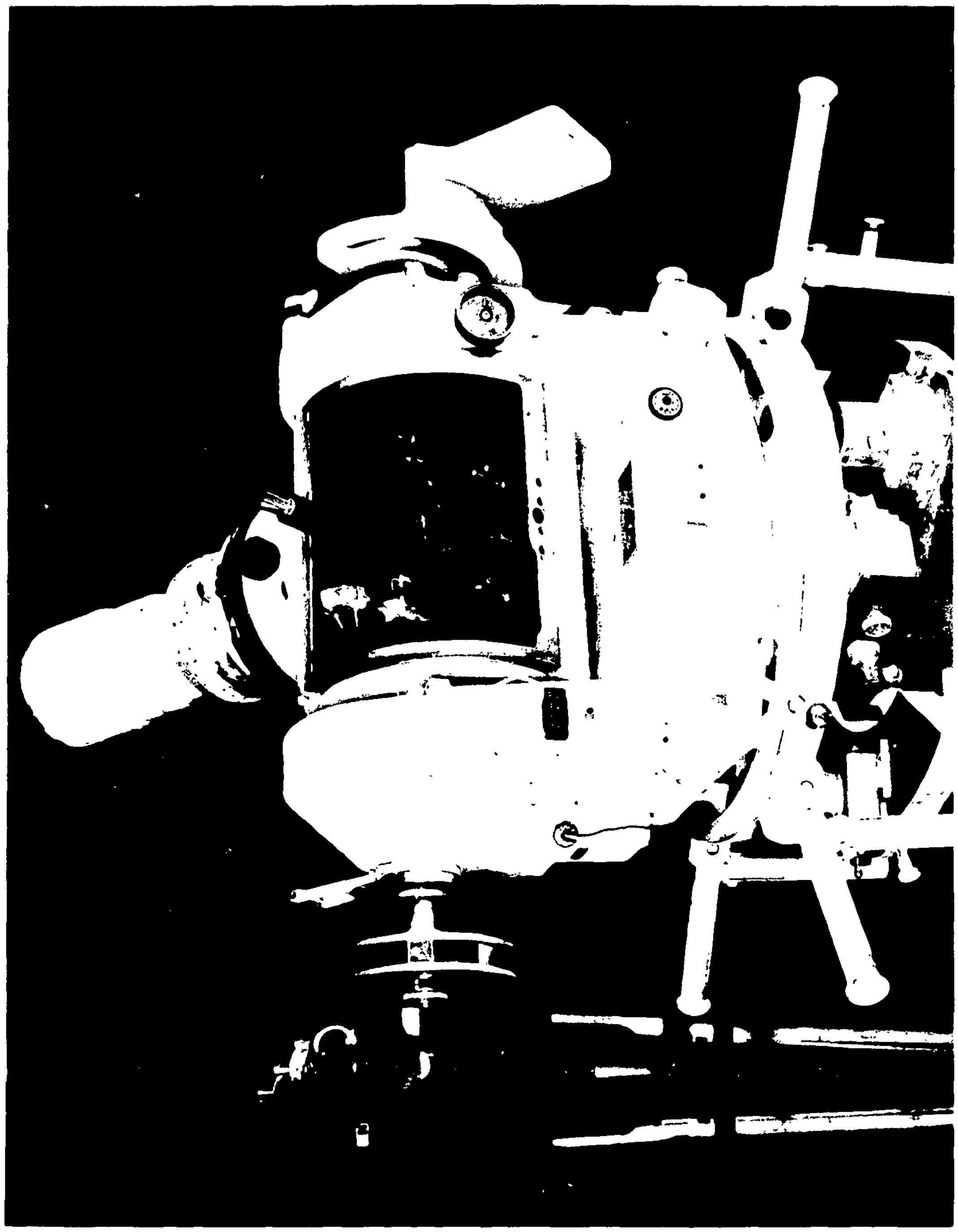


FIG. 9. Equipment Alignment, Elevation Dial Eccentricity.

E. Align the autocollimator with the polygon.

1. Place the autocollimator to the rear of the cinetheodolite and level and adjust the autocollimator to the same height as the elevation axis.

2. Rotate the camera and autocollimator jointly until the autocollimator appears lined up with the polygon.

3. Rotate the polygon so that a face will reflect the autocollimator light circle slightly higher than the autocollimator and locate the circle of light in the eye.

4. With the eye lined up on the circle of light, rotate the camera in azimuth so that the light is positioned directly over the autocollimator. This adjustment may require a further rotation of the autocollimator.

5. Rotate the polygon to bring the circle of light into the autocollimator field of view. If the light does not come into the field of view, repeat adjustment 4.

6. Tighten down the polygon and autocollimator.

F. When the above adjustments have been made so that the crosshair falls on the reading scale, rotate the camera in elevation and note the travel of the vertical crosshair as the light is reflected from successive faces of the polygon. This travel should not exceed 1/2 the reading scale. Reduce this travel by 'urther adjustment of the polygon.

1. Note the direction that the travel takes, and with the face of the polygon which produces maximum travel facing the polygon, adjust the screws on the polygon holder so that the image moves about half the distance back. Repeat this adjustment until the image remains within half the scale for 120 degrees of rotation of the elevation axis.

2. After adjusting the polygon, the autocollimator is adjusted in azimuth to center the image.

G. After the collimator and polygon have been aligned, check the zero setting of the internal elevation dial, make final adjustments to the polygon and collimator, and tighten all holding screws and clamps.

4. Recording measurements (see Sample Data Sheet #3)

A. Record on the data sheet the first and second faces of the polygon used to reflect autocollimator light, and the polygon number.

B. Draw an arrow representing the autocollimator on the picture in the upper-right-hand corner on the data sheet.

C. Increments of 15 degrees are set in on the internal elevation dial as read through the microscope. These settings should be made as close as possible.

D. For each setting the autocollimator is read, three sets of readings are taken up, down, and up for settings from zero to 120 degrees.

5. Mk 5 elevation dial eccentricity measurement

A. With the camera loaded with film (see Azimuth Dial Eccentricity, Step 5, p. 22), view the dial through the scale optics and set the dial on zero. Repeat settings in 15-degree increments from zero to 180 degrees.

B. For each setting, take a group of pictures in the following manner:

1. Turn on shutter motor switch and allow several flashes of flash lamps to over-expose one frame of the film.

2. Turn off shutter motor switch and turn on camera motor switch.

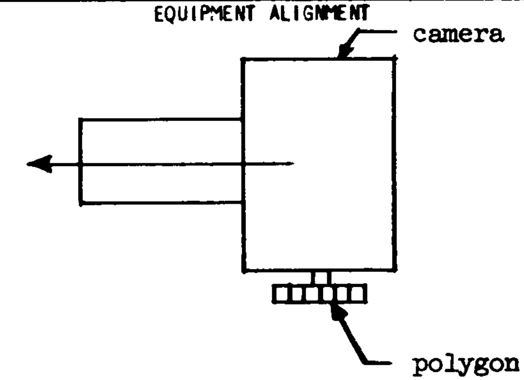
3. Hand pulse several frames using the single frame push button switch.

4. Switch synch-operate switch to the OFF position and hand pulse one or two frames.

C. The film is processed and sent to the Assessment Division. TN 3063-68, footnoted on page 22, outlines this procedure.

ELEVATION DIAL ECCENTRICITY - CALIBRATION DATA SHEET NO. 3
IIND NOTS 4120/7 (9-61)

CAMERA NO.		REMARKS	EQUIPMENT ALIGNMENT
CAMERA CODE	CAMERA LOC		
DATE			
CREW			
POLYGON NO.			
1ST FACE	2ND FACE		



DRAW IN ARROW FOR AUTOCOLLIMATOR.

MEASUREMENTS

DEGREES	ELEVATION DIAL θ_E	AUTOCOLLIMATOR READINGS UP	DOWN	UP			AVERAGE	POLY. CORR.	CORRECTED READINGS
0									
15									
30									
45									
60									
75									
90									
105									
120									

NOTE: READINGS ACROSS THE PAGE SHOULD BE WITHIN A TEN-SECOND RANGE.

Lens Tube Sag Due to Gravity

1. Equipment

   A. Reticle (Fig. 10, insert)

   B. Autocollimator, long autocollimator plate, transformer

   C. Tripod, Mitchell tripod head, spider

   D. Farrand vertical leveling (pendulum) mirror

   E. Tool box

   F. Metric (kilogram) weights and hanger

   G. Spot light and 1 x 1-ft piece of white paper (for folded type optics)

   H. Reversion level (see Fig. 11, p. 33)

2. Positioning and mounting of the equipment

   A. Mount the reticle in the place of the aperture plate.

   B. Mount the autocollimator in front of and pointing into the cinetheodolite optics.

   C. Attach the reversion level to the dovetail of the tracking optics (telescope has been removed) so that it is parallel to the optic axis. Remove all counter weights on the dovetail bracket.

   D. Place the pendulum mirror in front of the autocollimator. (It has been found that supporting the pendulum mirror on the long autocollimator plate causes a deflection of the Mitchell tripod. As a result, a mounting bracket has been fabricated which mounts in the right-hand dovetail. This holds the pendulum mirror so that the levelness of the autocollimator can be maintained.)

3. Alignment of the equipment

   A. Nonfolded type of optics

      1. With the cinetheodolite optics approximately leveled, point the autocollimator into the central region of the objective lens and level it with the pendulum mirror. The reflected and outgoing crosshair images should be superimposed at the center of the scale.

      2. Remove the pendulum mirror and adjust the cinetheodolite in azimuth to center the vertical member of the reticle crosshair in the autocollimator field of view.

      3. Adjust the cinetheodolite in elevation so that the horizontal member of the reticle crosshair is approximately centered in the autocollimator scale. (Note that the center of the scale has been made the level reference.) Lens tube sag registers on the autocollimator scale as

a positive reading relative to the level reference.*
Collimation error between the autocollimator and the cinetheodolite can be minimized by making the initial adjustment of the reticle crosshair slightly positive. Lens tube sag causing rotations of the optic axis does not generally exceed one minute of arc.

4. Level the reversion vial.

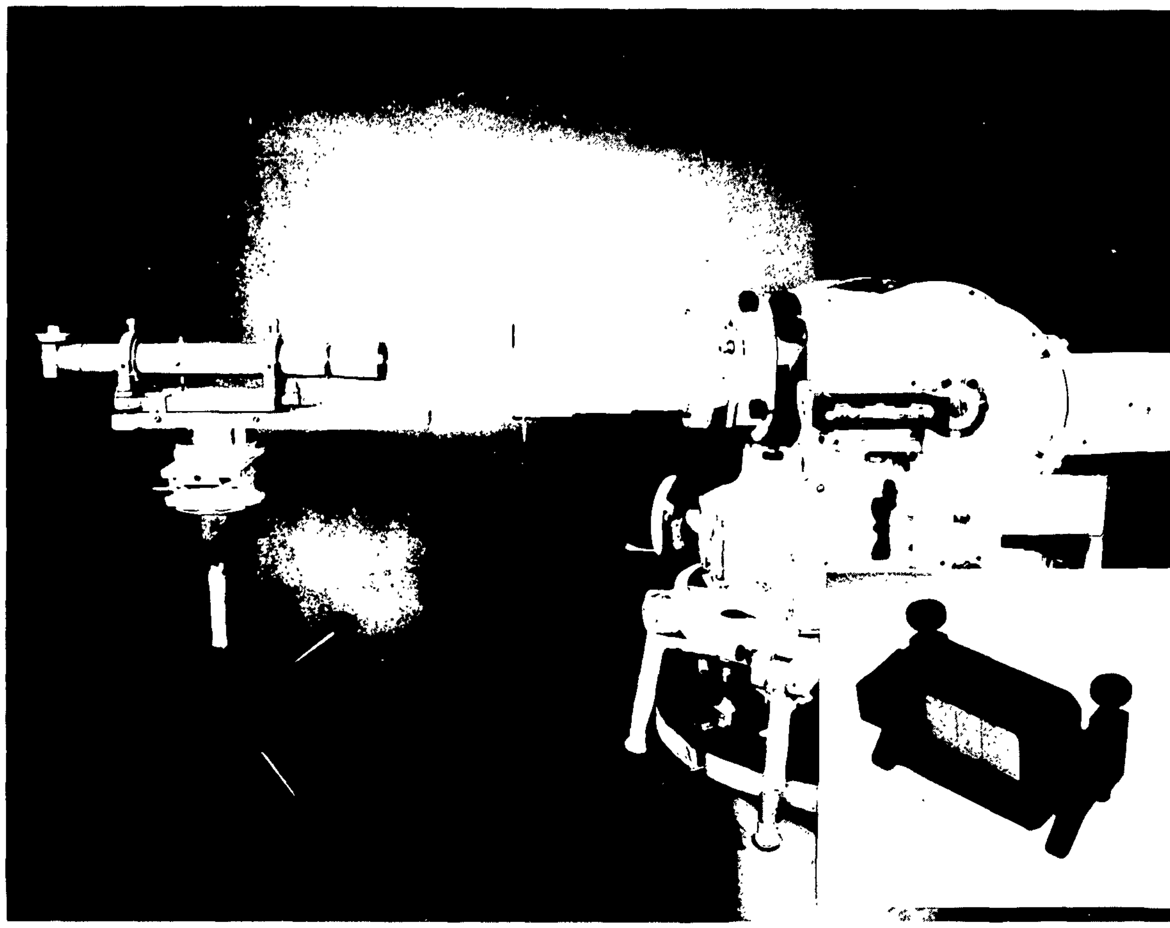


FIG. 10. Equipment Alignment, Lens Tube Sag Due to Gravity. Shown in inset is special reticle used for measuring lens tube sag.

*To obtain the true angular change, multiply the readings by two because the crosshair image one sees is the direct image from the reticle mirror in the focal plane of the camera and not the reflected image of the crosshair in the autocollimator.

B. Folded type optics:

1. The alignment procedure for this case is the same as above except that the autocollimator is translated horizontally to the annular opening of the cinetheodolite optics.

2. An illuminated piece of white paper placed within the field of view of the cinetheodolite optics renders the reticle crosshair visible in the autocollimator. (Pointing the optics out of the astrodome opening will also serve as a suitable light source.)

4. Recording measurements

A. Check the levelness of the autocollimator and the tightness of all holding screws.

B. Record the autocollimator readings on Calibration Data Sheet #4.

C. Rotations to the dumped position are made by:

1. Rotating 180 degrees in azimuth;

2. Rotating in elevation to the dumped position so that the reversion vial is level.

D. Repeat steps A, B, and C for a minimum of three measurements. If readings do not repeat to within three to five seconds of arc, the number of measurements should be increased. Check the zero reference with the pendulum mirror each time the autocollimator is read.

E. After the above measurements have been made apply torques to the lens tube in the forward and in the dumped positions, using the kilogram weights.

F. The torques are applied approximately at the position of the front element, and either up or down. As a check this may be applied in the reverse direction if the results of the measurements are unreasonable.

G. Deflections resulting from the applied torques are recorded on Data Sheet #4.

1. F_1, F_2, ... in the forward position.

2. D_1, D_2, ... in the dumped position.

LENS TUBE SAG DUE TO GRAVITY - CALIBRATION DATA SHEET NO. 4

LIND NOTS 4120/8 (9-61)

CAMERA NO.		MEASUREMENTS				
		AUTOCOLLIMATOR READINGS		S_f	S_d	$S_f + S_d$
CAMERA CODE	CAMERA LOCATION	FORWARD = F	DUMPED = D			
DATE						
LENS NO.	LENS CODE					
CREW						
REMARKS						
		S_f = F - 5' 0"	S_d = D - 5' 0"	AVERAGE $(S_f + S_d)$ =		

WT kg	AUTOCOLLIMATOR READINGS FORWARD	BUMPED	RATIOS
1	F_1 =	D_1 =	
2	F_2 =	D_2 =	$R = (F_2 - F_1)/(D_2 - D_1)$ =
3	F_3 =	D_3 =	$R = (F_3 - F_1)/(D_3 - D_1)$ =
4	F_4 =	D_4 =	$R = (F_4 - F_1)/(D_4 - D_1)$ =
			AVERAGE R =

CALCULATIONS

SAG IN FORWARD POSITION = S_F $\qquad S_F = -S'_F = -\dfrac{2R\,(S_d + S_f)}{(R+1)}$ = SEC. = DEG.

SAG IN BUMPED POSITION = S_D $\qquad S_D = S'_D = \dfrac{2\,(S_d + S_f)}{(R+1)}$ = SEC. = DEG.

$S_F = -RS_D$

$\phi_s = \dfrac{S_D + S_F}{2}$ = DEG.

Standards Error Measurement

1. Equipment

   A. Reversion level and bracket (The type of bracket to be used will be determined by the type of camera being calibrated.)

   B. Small mirror for reading reversion vial

2. Position and mounting of equipment

   A. Kth 41 and Mk II cinetheodolites

      1. Mount the level on the bracket.

      2. With the camera in the forward position (see Fig. 11) remove the lens shade and mount the bracket on top of the lens base with the two adjusting screws which hold the lens shade.

   B. Mk V cinetheodolite

      1. Mount the level on the bracket.

      2. Remove two bolts from the counter weight on the rear of the camera housing.

      3. Bolt bracket to camera housing using these same two bolts.

3. Alignment of equipment

   A. Level the camera.

   B. Elevate the camera to 90 degrees and adjust the reversion level to levelness using the brass adjusting screws (see Fig. 12a). (This adjustment makes the level vials parallel to the vertical plane which passes through the elevation axis when the optic axis is horizontal.)

   C. Bring the elevation axis back to zero and level the reversion level with the brass adjusting screws so that scales "A" and "B" can be read. The reversion level is labeled with an arrow pointing toward the brass adjusting screws. The scale to the left of the arrow is scale A, and to the right is scale B. The bubble should be read from the left to the right in the direction of the arrow (Fig. 12a). Be certain both brass adjusting screws are tight after leveling.

   D. Rotate the camera 180 degrees in elevation and note if scales A′ and B′ can be read. If not, adjust brass adjusting screws so that A′ and B′ can be read.

   E. Rotate the camera back to forward position and determine if scales A and B can be read.

   F. Repeat steps C and D until level scales can be read in forward and dumped positions. (If Step E is impossible, then the standards error is too large to be measured by this method.

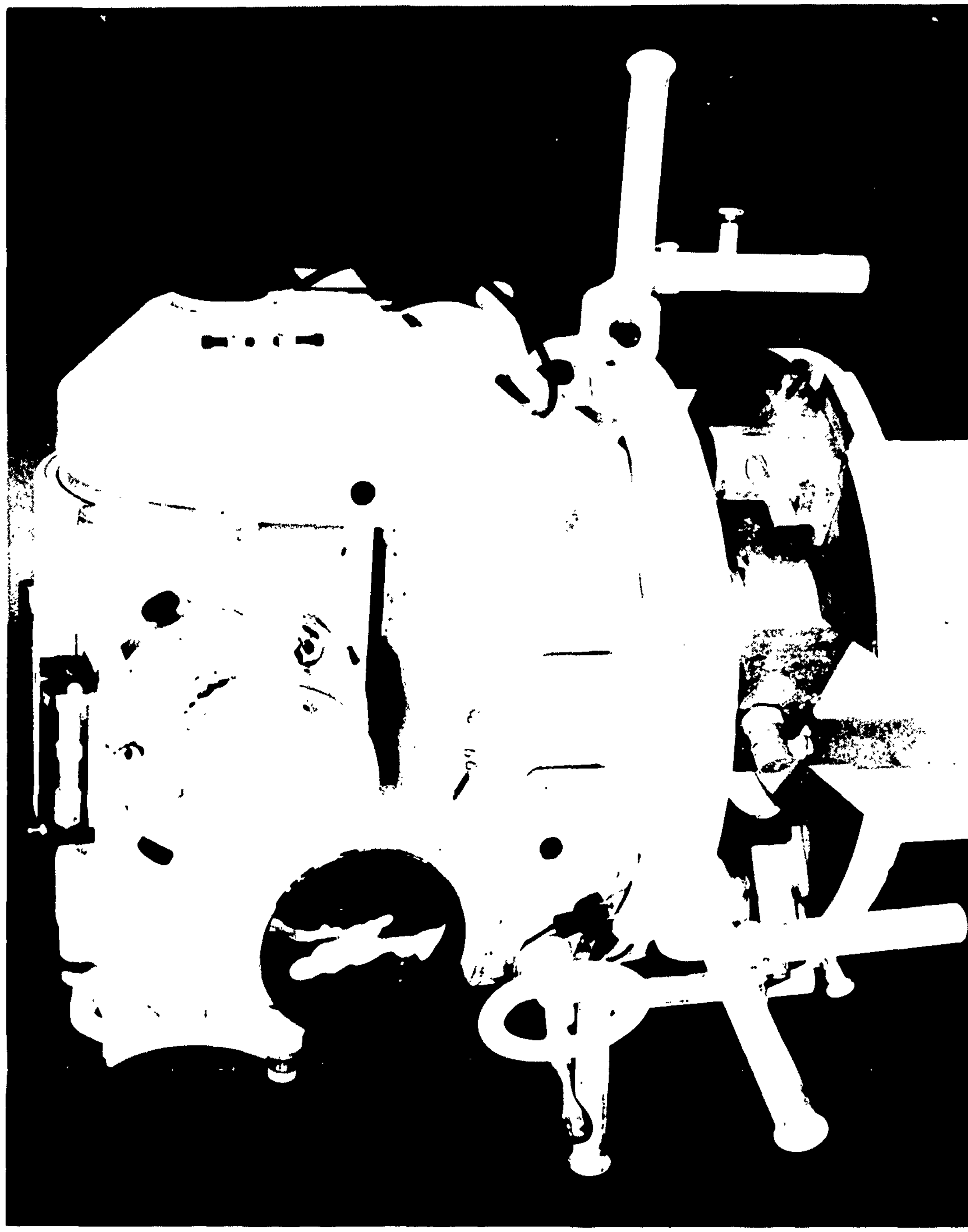


FIG. 11. Equipment Alignment, Standards Error.

4. Reading the bubble

A. Standing in front of the camera at (0), Fig. 12, with the camera in the forward position, the bubble will appear to the observer as shown in Fig. 12a. The arrows with the tails indicate the direction of the optic axis of the camera, Fig. 12b. The lines on the scales are numbered 1 to 13 reading from left to right. The "X" denotes the end of the bubble with the brass adjusting screws. Estimate readings of the scales to the nearest 1/10th of a scale division, reading from left to right as indicated by the arrows without tails in Fig. 12b.

B. Having determined the initial reading of the scale A on the level vial (see Section 3, paragraphs D and E, p. 32), and keeping this reading in mind, level the bubble so that the bubble is centered and record the reading on scales A and B, denoting them as A_o and B_o, on Data Sheet #5. (See G, Step 5, below.) Record the azimuth reading on the external scale as a_o.

C. Readjust the level vial to position previously determined in Section 3, D. Read A and B and record.

D. Rotate the camera 180 degrees in elevation (to the dumped position) to position (2) indicated in Fig. 12b. Read A′ and B′ and record, reading from right to left. Figure 12b is drawn as though the observer remained stationary and only the camera moved. In order for the observer to read the bubble, the observer will have to move so that he is at (0) facing the arrow with the tail. Thus the direction of reading changes to right to left for scales A′ and B′.

E. Rotate the camera 180 degrees in azimuth to $a_o + 180$. The 180-degree rotation in azimuth is read on the external camera azimuth scale. The bubble is now in position (3). Read A′ and B′ and record, reading from right to left.

F. Rotate the camera 180 degrees in elevation to the forward position (4). Read A and B and record, reading from left to right.

G. In summary, the order of reading and recording is:

1. Elevation angle is zero degrees, vial is level, azimuth angle is a_o, read scales A and B to determine A_o and B_o.

2. Elevation angle is zero degrees, vial is not level, azimuth angle is a_o, read scales A and B. (If the standards error is small, it is then possible to make measurements without misleveling the vial, i.e., $A_o = A$, and $B_o = B$.)

3. Elevation angle is 180 degrees, azimuth angle is a_o, read scales A′ and B′.

4. Elevation angle is 180 degrees, azimuth rotated 180 degrees to $(a_o + 180)$, read scales A′ and B′.

5. Elevation rotated to zero degrees, azimuth angle is $(180 + a_o)$, read scales A and B.

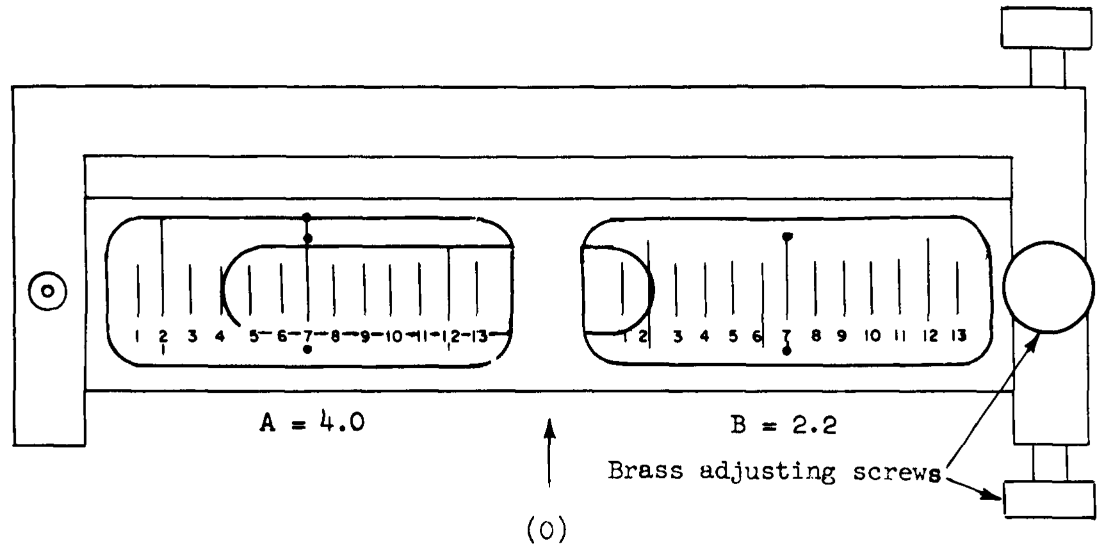


FIG. 12a. Labeling of the Reversion Level Vial.

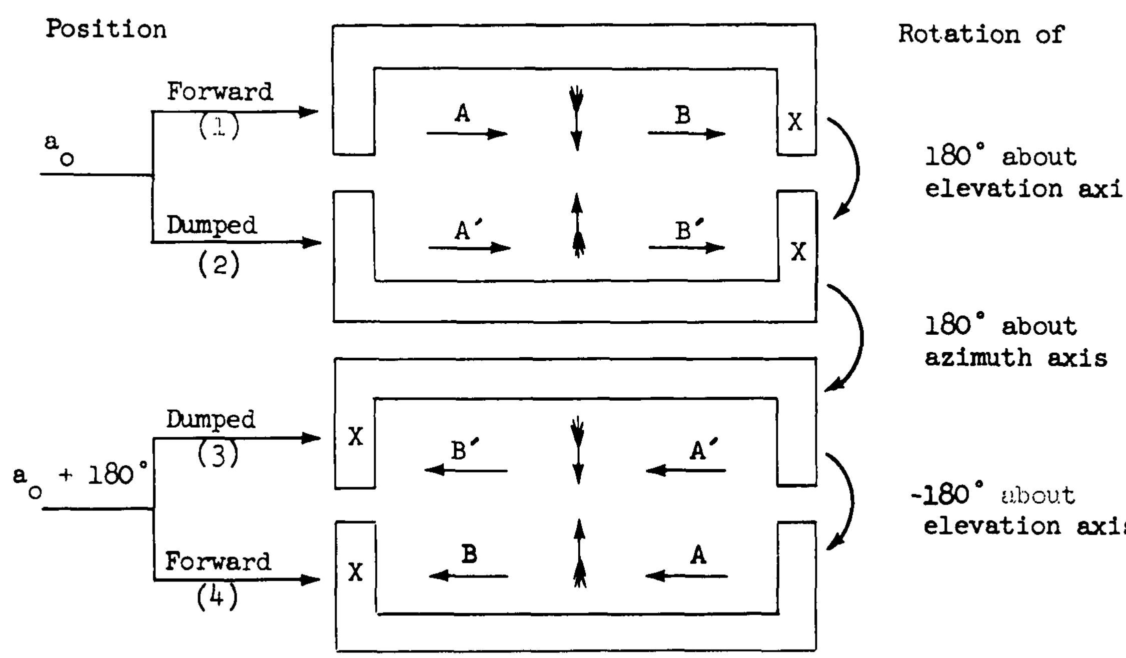


FIG. 12b. Using the Reversion Level Vial.

FIG. 12. Standards Error Measurements.

5. Recording the measurements

   A. Enter the above readings of the bubble as they are defined above. (See sample Calibration Data Sheet #5.)

STANDARDS ERROR – CALIBRATION DATA SHEET No. 5
IIND NOTS 4120/9 (9–61)

CAMERA NO.		REMARKS
CAMERA CODE	CAMERA LOCATION	
DATE		
CREW		

MEASUREMENTS			CALCULATIONS
1. CAMERA IN FORWARD POSITION:	a_0 =	DEG.	1. CALCULATE THE FOLLOWING VALUES:
BUBBLE READINGS:	A_0 =		A) $\gamma_1 = A_2 + A_1 - 2A_0$ =
	B_0 =		B) $\gamma_2 = B_2 + B_1 - 2B_0$ =
	A =	= A_1	C) $\gamma_3 = A_4 + A_3 - 2A_0$ =
	B =	= B_1	D) $\gamma_4 = B_4 + B_3 - 2B_0$ =
2. CAMERA IN DUMPED POSITION:	a_0 = SAME		E) $s = \frac{10.5\,(\gamma_1 + \gamma_2 + \gamma_3 + \gamma_4)}{8}$ = ______ SEC.#
BUBBLE READINGS:	A' =	= A_2	
	B' =	= B_2	F) s/3600 = DEGREES
3. CAMERA IN DUMPED POSITION:	$a_0 + 180^0$ =	DEG.	2. *IF S IS NEGATIVE $\|S\| = 90 + s$ = DEG. } CHOOSE ONE
BUBBLE READINGS:	A' =	= A_3	IF S IS POSITIVE $\|S\| = 90 - s$ = DEG. }
	B' =	= B_3	
4. CAMERA IN FORWARD POSITION:	$a_0 + 180^0$ = SAME		
BUBBLE READINGS:	A =	= A_4	# 10.5 IS A CALIBRATION CONSTANT OF THE REVERSION VIAL USED AT NOTS.
	B =	= B_4	*THE HIGH STANDARD IS IN THE SAME DIRECTION AS THE BUBBLE DRIFT WHEN CHANGING THE BUBBLE SETTING FROM A_0 TO A_1.

SECTION IV

REPORTING CALIBRATIONS

This section precedes the section describing calculations in order to point out a few pitfalls which can be encountered while calculating the calibration constants. The purpose is to correlate the measurements, calculations, and reporting procedures to give the proper interpretation of the calibration data.

Appendix D is included to give an example of previously reported calibration data for Kth 41 number 445. The format for this report has evolved from reporting experience and gives the measurements, computed constants, and usually graphs of the measurements where applicable.

In the case of Mark V dial eccentricity or principal distance only a roll of edited film is forwarded to the Data Analysis Branch.

The film exposed to determine principal distance is edited to insure that at least 40 measurable images of the target are recorded so that they are distributed rather evenly across the film, and that corresponding to each image, an azimuth dial picture was recorded.

The film exposed to determine dial eccentricity is edited to insure the exposure of all the dial increments and that for each increment, at least one exposure shows both dial marks. The film is read on the Iconolog and the punched cards are used as direct inputs to program 7403 which computes the dial eccentricity. T.N. 3063-106, footnoted on page 13, explains the use of the program.

The report for the standards error gives a value $|S|$ which is an angle between the elevation axis and the azimuth axis as previously defined. On Data Sheet #5 under Calculations, Step 1, F) gives the value of s in degrees with the proper sign as defined in T.N. 303-1, footnoted on page 9.

Lens tube sag due to gravity, S_F, equals the sag when the cinetheodolite is in forward position, and S_D, the sag in the dumped position. The sag decreases the elevation angle in the forward position and increases it in the dumped position. Experience indicates that the sag will have the same affect no matter what type of optics, i.e., the translation of the nodal point of the optical combination is the only consideration.

Reporting of the mislevel involves an interpretation of the measurements with respect to the direction the autocollimator was pointed. Measurement of deflections of the optic axis of the cinetheodolite due to azimuth bearing wobble should be measured with the autocollimator facing the rear. An effective increase of the elevation angle is recorded as a positive going reading.

Parallel to the elevation axis, deflections due to azimuth bearing wobble introduce variations to the standards error correction, and to have the proper sign, the autocollimator should point to the right (away from the tracking optics).

The picture on the data sheet indicates the direction the autocollimator was pointing when measurements were taken. If the sign of the calculated data requires changing, due to reversed directions of equipment, it can be done by introducing a minus sign to CONV (CONV is defined in Appendix C). The important thing to remember is that the error and the reported correction should be in phase.

There is no ambiguity in reporting the correction to the azimuth dial readings. The computed constants always have the proper sign and are added forthright to correct the azimuth angle when CONV is made positive.

The computed constants experience different signs between the two possible positions of placing the autocollimator when measuring the elevation dial eccentricity. The correct signs result from placing the autocollimator to the rear of the cinetheodolite. The criteria indicate where to place the autocollimator so the scale reads in a sense opposite to the error it is measuring. This is brought about by the inversion of the image by the autocollimator objective. If the autocollimator has been set up forward to the cinetheodolite, merely render the sign of CONV negative.

It should be pointed out that the autocollimator in this report refers to the Hilger-Watts type with filar eye piece, having a scale which reads 0 to 10 from bottom to top or left to right and this introduces the above sign convention.

The actual report of a calibration consists of a cover sheet, one copy of the data sheet, and a final page of graphs and constants when applicable (Appendix D). These reports are seimpermanent records when calibrations are performed on a continuing basis.

SECTION V

CALCULATIONS

This section discusses the procedure for calculating the calibration constants with which cinetheodolite data is corrected. These constants are presented in a form which is usable to the IBM cinetheodolite solution. All constants are given in degrees of arc except the principal distance.

Principal Distance

The series of pictures taken by panning the target are measured on the Iconolog film reader. Each measurement consists of a distance measurement X and an azimuth angle A. These measurements are paired so that they are approximately symmetrical about the center of the film frame (vertical fiducial reference). Taken in pairs in this manner, and by subtraction, we have values which can be tabulated as:

$$X_i = (X_2 - X_1)_i \qquad \text{and} \qquad \phi_i = (A_2 - A_1)_i$$

By the first method of calculation:

$$P = \frac{1}{n} \sum_i \frac{X_i}{2 \tan \frac{\phi_i}{2}} \qquad i = 1, 2, \ldots, n \text{ pairs of measurements.}$$

For this calculation, n should be at least 20 pairs of readings. For the second method[13] of calculation, the following formula gives the principal distance:

$$P = \frac{\sum_i X_i \tan \frac{\phi_i}{2}}{2 \sum_i \tan^2 \frac{\phi_i}{2}} = K \frac{\sum_i Ix_i I\phi_i}{\sum_i I\phi_i^2} \qquad \text{and} \qquad K = \frac{\ell k}{C}$$

where: Ix_i = Iconolog counts in X_i

$I\phi_i$ = Iconolog counts in ϕ_i

C = 0.01746

ℓ = Iconolog constant (millimeters/count)

k = Iconolog constant (counts/degree).

[13] Mace, R. W., T.N. 3063-73, Appendix I

IBM Calculations for Harmonic Analysis of Dial Eccentricity[14,15] and Axial Mislevel and Rollerpath Errors

The equations for calculating the constants Δ_j and β_j mentioned in Section II are discussed in several other reports, some of which are T.N. 3063-17, footnote 2, page 4; T.N. 3063-7 and IDP 102, footnote 3, page 5; and T.N. 3063-58, footnote 6, page 8. Technical Notes 3063-71 and 3063-75 are manuals of instruction for entry of measurements onto IBM punched cards.

Program 8702 is designed to be used only when the measurements are made over equal angular increments for a complete rotation of the dial. Program 8705, a least squares method, does not require this condition but requires the angles to be read into the computer. If the initial dial reading is not zero and the angular increments are equal, program 8702 may be used with the THETAP entry on the first card.

The measurements consist of a set of dial readings with corresponding autocollimator readings (Section III). The autocollimator readings are an average of three measurements. This data is entered into the IBM on punched cards in the manner described in Appendix C. Appendix C consists of excerpts from T.N. 3063-71 and T.N. 3063-73 which describe the use of programs 8702 and 8705.

If measurements for mislevel and azimuth dial eccentricity have been made in accordance with Section III, and use is made of program 8702, there are n = 13 measurements giving N = 12, (N = n - 1 measurements), L = 1 (when the autocollimator readings have been averaged), CONV = 2.7777777E-05, $M = \frac{N-1}{2} = 5$ (three orders are requested),[16] and K = 1 (request for all orders up to M). The entry THETAP on input card #1 is left blank if the initial dial reading is zero.

The measurements for elevation dial eccentricity result in nine averaged autocollimator measurements corresponding to nine dial angles starting usually with zero degrees and running through 120 degrees. For this calculation, using program 8705 (note that here N = n):

N = 9
M = 4 (3 orders are calculated)
CONV = 2.7777777E-05

[14] Bondelid, M. A., Mace, R. W., Spectrum Analysis of Biased Mechanical Errors (NOTS IBM PROGRAM 6402), T.N. 3063-71, Mar 1959.

[15] Bondelid, M. A., Josephson, J. E., Least Squares Multiple Order Harmonic Analysis (Uneven θ Increments & Fractional 360° Rotation) NOTS IBM PROGRAM 6405, T.N. 3063-75, Mar 1959. Programs 6402 and 6405 have been recompiled under prefixes 8702, 8705 and combined with prefix 8706 into program 7402.

[16] This value for M is a theoretical one. In practice, twelve data points are not sufficient to determine a fifth-order harmonic.

The usual procedure is to determine the constants and enter them and the measurements on a Fortran coding form. The information on the coding form is then transferred to the IBM cards.

Programs 8702 and 8705 print out on line values A_j,[17] B_j, C_j, Δ_j, and β_j. Only the Δ_j and β_j constants are used in the IBM-709 cinetheodolite reduction; however, all of the constants are reported. All of the constants are in degrees of arc.

In summary, if measurements are made according to Section III, the inputs are:

For 8702	Card 1.	Constants N, L, CONV, THETAP
	Card 2.	Autocollimator measurements
	Card 3.	Constants M, K
For 8705	Card 1.	Constants N, M, CONV
	Card 2.	Autocollimator measurements
	Card 3.	Dial readings
	Card 4.	Dial readings.

The autocollimator measurements should be corrected for polygon errors prior to being used in the above programs. The polygons in use have been calibrated and the corrections appear in T.N. 3063-80 and also in T.N. 3063-102[18]. T.N. 3063-80 gives the method for calibrating a polygon. The columns headed polygon corrections on the data sheets #2 and #3, Section III are for entry of the polygon calibrations. The autocollimator readings are entered on IBM cards without the decimal point showing. The adjustment for the decimal place is made with the constant CONV.

Standards Error

Measurements consist of a_o, $a_o + 180$, A_o, B_o, A_1, through A_4, and B_1 through B_4 which appear on Calibration Sheet No. 5. At the bottom of this sheet under calculations are the equations required to calculate the standards error. A derivation of equations (a) through (e) appears in Appendix E.

---

[17] The value of A_j is the same for all orders. It is a constant pertaining to the measuring instrument, not the cinetheodolite.

[18] Rockwell, R. L., Calibration of the Hilger-Watts Polygon, T.N. 3063-80, Aug 1959, pp. 7 and 8, and
Josephson, J. E., and others, Calibration Data, Hilger-Watts Polygons, T.N. 3063-102, June 1960.

Since other methods are sometimes used to measure standards error, a brief discussion is given here as to references covering the subject.

If measurements are made with the apparatus setup described in T.N. 3063-18 (footnote 4, page 5), the mathematical reduction on page 2 of that report is applicable.

If measurements are made with the apparatus setup described on pages 5 and 6 and shown in Fig. 4 of T.N. 3063-45 (footnote 10, page 11), at elevation angles of zero degrees and 180 degrees, use the solution on page 7 of that report.

If, however, the standards error is determined by a least-squares fit to the circular configuration of data points, use the solution given in T.N. 3063-81[19]. The computations are made by using IBM program 6413 (subsequently recompiled under the prefix 9013), as shown in T.N. 3063-83[20].

The method outlined in T.N. 3063-18 allows for using instruments having smaller reading errors but does not correct for mislevel values and has been superseded by the method described in Section III. The method in T.N. 3063-45 is laborious and involves complicated calculations, but does present a method to measure elevation bearing wobble.

Lens Tube Sag Due to Gravity

The calculations to obtain the lens tube sag can be performed on data sheet #4. The level reference reading of the autocollimator remains constant. The values S_f and S_d are the differences from the level reference reading of the autocollimator of the forward and dumped readings. The average value of $(S_f + S_d)$ is used to reduce the effect of reading errors.

The ratio R is found by comparing deflections of the optic axis in the forward position to those in the dumped position when bending moments are applied to the lens tube. Data sheet #4 is arranged so that differences are calculated for successive autocollimator readings, and R is averaged to reduce the effect of reading errors.

---

[19] Mace, R. W., Least Squares Solution of a Circular Configuration of Data Points, T.N. 3063-81, Aug 1959.

[20] Bondelid, M. A., Standards Error of Instrument Mounts (NOTS IBM PROGRAM 6413), T.N. 3063-83, Aug 1959, p. 7. For this calculation NOTS IBM PROGRAMS 8702 or 8705 are used with NOTS IBM PROGRAM 6413. See also Notes on Interpretation of Autocollimator Data for Orientation of an Elevation Axis, by Bondelid, M., T.N. 3063-84, Aug 1959, page 7.

SECTION VI
DISCUSSION

Pertinent to this report is the validity of the measurements once they have been made. The following values are quoted from experience rather than theory. The reading errors of the autocollimator have a first standard deviation of 1.0 ± 0.5 seconds of arc depending on the reader. This imparts the same accuracy to the polygon corrections.

The following values for repeatability of readings seems to emerge after about two years' experience with optical measurements:

Mislevel and wobble	= ± 2 sec of arc
Dial Eccentricity	= ± 5 sec of arc
Standards Error	= ± 3 sec of arc
Lens Bending	= ± 2 sec of arc

The above values establish ranges for what is considered good calibration data. If readings will not repeat within these ranges, it is usually due to some mechanical fault and is brought to the attention of the Opto-Mechanical Branch of the Instrument Development Division.

The above repeatability of measurements imposes limits of significance on the calculated calibration constants of the same range, especially second- and third-order corrections.

The standards error measurements are quite sensitive to thermal effects. For example, electric lights in an astrodome seem to affect the length of the bubble. This can be overcome by positioning the cinetheodolite so that heat transfer is equalized in the forward and dumped positions.

Another effect which has prevented measuring the standards error of instruments in astrodomes is that of high velocity gusts of wind causing the bubble to shift several seconds of arc.

These two effects are evident when the difference $(A_4 - A_1)$ does not equal $(B_4 - B_1)$ within the limits of repeatability.

The following weaknesses of the calibration procedure stand out as needing further attention when and if greater accuracy is required of

the Mark V or some other instrument. Reading errors could certainly be reduced. The reading errors of reading the film in Mark V dial calibrations is probably no better than the autocollimator method. Probably the single greatest source of error in the present procedure stems from the dependence on the eyes and the effects of its fatigue.

As of this date a satisfactory method for rapidly measuring elevation bearing wobble has not been established.

The ability to present an estimate of weighting factors pertaining to data from a given cinetheodolite is currently possible. Where orthogonal components of errors are measured simultaneously, variances can be computed for the azimuth and elevation angles.

No definite criteria have been established regarding the allowable magnitude or form of errors. By form is meant the effect of wobble components. If the errors in an instrument are definitely repeatable they are considered usable in some phase of the operation.

Appendix A

STANDARDS ERROR TRANSFORMATION

Following is a derivation for equations showing the effect of standards error on the dial readings A_o and E_o. Figure 13 shows rotations of the coordinate camera axes necessary to transform the optic axis J or j into $\vec{r}$. The transpose matrices for these rotations taken in reverse order rotate $\vec{r}$ instead. For the present purposes, $\vec{r}$ will be rotated to coincidence with J defining an initial condition for the camera of having been rotated through the azimuth angle A. This is allowable since δA is independent of A.

In the I, J, K system, $\vec{r}$ is transformed by the matrix operation

$$\begin{bmatrix} 0 \\ \cos E \\ \sin E \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos E & -\sin E \\ 0 & \sin E & \cos E \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

the assumption is made that there are no tracking errors involved. The object is to quite simply investigate the rotations of the optic axis in the (I, J, K) system and in the (i, j, k) system, and compare direction cosines.

Taking into account the standards error corrections, the matrix operation is

$$\begin{bmatrix} -\cos\delta A \sin s \sin E_o - \sin\delta A \cos E_o \\ -\sin\delta A \sin s \sin E_o + \cos\delta A \cos E_o \\ \cos s \sin E_o \end{bmatrix} =$$

$$\begin{bmatrix} \cos\delta A & -\sin\delta A & 0 \\ \sin\delta A & \cos\delta A & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos s & 0 & -\sin s \\ 0 & 1 & 0 \\ \sin s & 0 & \cos s \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos E_o & -\sin E_o \\ 0 & \sin E_o & \cos E_o \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

Note here that there is a constraint which produces the rotation $-\delta A$ about K thus establishing an order of operation. The sign of δA is determined by the definition of s.

The equivalency of the above operations yields, upon equating the column matrices on the right, the equations

$$\sin E = \cos s \sin E_o ,$$

$$\tan\delta A = -\sin s \tan E_o .$$

The magnitude of the standards error is small, usually less than one minute and the approximation can be made that $\cos s = 1$ and $\sin s = s$ (s in radians) so that

$$\sin E \cong \sin E_o ,$$

$$\tan\delta A \cong -s \tan E_o .$$

This shows that the standards error has the greatest influence on the azimuth angle and very little on the elevation angle. The effect on the azimuth angle is not gross until the elevation angle approaches the zenith angle.

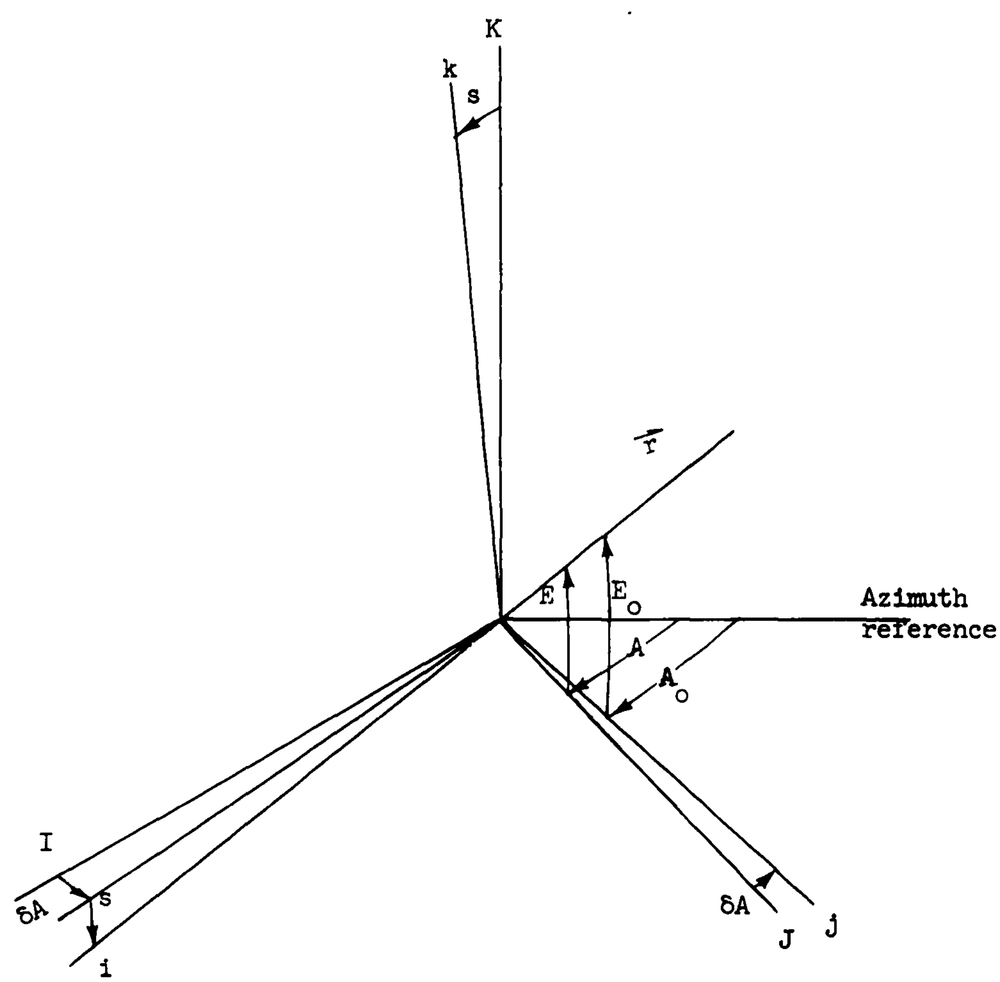


FIG. 13. Standards Error Transformations.

Appendix B

LENS TUBE BENDING DUE TO GRAVITY

Following is a short derivation for the correction to the orientation angle 0_E (or 0_H) if the lens tube sag is not equal in the forward and dumped positions. Figure 14 gives the notation used in the equation.

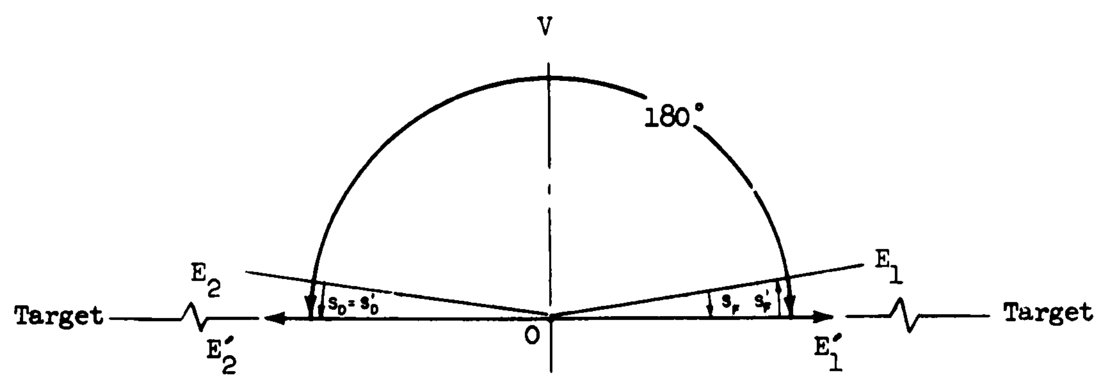


FIG. 14. Lens Tube Sag Due to Gravity.

For the purpose of this derivation, the vertical will be assigned the dial reading

$$V = \frac{E_1 + E_2}{2},$$ and the positive direction is counterclockwise,

E_1 and E_2 being the readings of the dial in the forward and the dumped positions, when the optics have been sighted in on the same target. This definition does not account for the presence of lens tube sags S_F and S_D, for the forward and dumped positions respectively.

To sight on the same target and account for sag, rotations are required to counteract the effects of the sag and different dial readings

$$E_1' = E_1 - S_F' \quad \text{and}$$
$$E_2' = E_2 + S_D'$$

are the result. The vertical dial reading, if computed as above, is

$$V' = \frac{E_1' + E_2'}{2} = V + \sigma_s$$

where

$$\sigma_s = \left(\frac{S_D' - S_F'}{2}\right)$$

This latter expression is used when computing O_E and is in error by the amount σ_s. Both sags are read as positive values.

In most cases $|S_F| \cong |S_D|$ and the value of σ_s is quite small.

Appendix C

USE OF PROGRAMS 8702 AND 8705

PROGRAM 8702

On the first card to be entered, following the program deck, values for four constants must be specified. These values depend on the experimental conditions. The constants are:

N — The number of evenly spaced readings per 360 degrees such that $0° \leqq \theta < 360°$. Maximum of 90 readings allowed.

L — The number of sets of N readings, up to 5 sets.

THETAP — Initial dial reading. If $\theta_o = 0$, omit THETAP. (Blank fields are read into IBM 709 as zero.)

CONV — The conversion factor, determined as follows:

The conversion factor depends on the units in which the data is obtained. Only 4 significant digits of the data are retained. The following table indicates the derivation of CONV for three types of reading instrument. The multiplication factor will be explained below.

Reading Instr.	Units	Multi. Factors	Conversion Factor	CONV
Iconolog	Degrees (.0xxxx)	10^5	1×10^{-5}	1.0E-05
Autocollimator	Seconds (xxx.x)	10^1	$\frac{1}{3600} \times 10^{-1}$	2.7777777E-05
SAMI	Inches (.xxxx)	10^4	$\frac{5.023}{3600} \times 10^{-1}$	1.3952777E-04

The IBM input card is divided into four fields and the appropriate values for N, L, CONV, and THETAP are entered with the following layout (place all numbers to the extreme right of each field):

Columns	1-5	6-10	11-24	25-33
Constant	N	L	CONV	THETAP
IBM Card	---xx	----x	-x.xxxxxxxE-0x	-xxx.0000

Use of the correct conversion factor changes all input data to degrees, and the coefficients will also print on-line in degrees.

The next set of cards contains the readings R_k. These readings must be adjusted by the multiplication factors listed in the above table, so that all R_k enter the IBM in the same form. The data is placed on the cards in the same order as it was recorded: the first set of N readings, followed by the second set, and so forth. The IBM input cards are divided into 14 fields of five columns each, and the data are entered into the cards with the following layout (place all numbers to the extreme right of each field; and if there are more than 14 numbers to be entered, all 14 fields must be used before the next card is punched): Negative or positive R_k are accepted.

Columns	1-5	6-10	11-15 ----------	65-70
Data R_k	±xxxx	±xxxx	±xxxx ----------	±xxxx

Following this is the set of cards which designates the orders of the harmonics. The number of cards depends upon the orders wanted. The maximum order is 44*. If all orders from one up to the highest order are desired, only one card is necessary. If only certain orders besides the first are desired, then one card is required for each order above the first. In this case, the first order will be calculated along with each higher order. If all orders are wanted, the two constants are M, the highest order desired (not to exceed 44), and K, which is set equal to 1. For special orders, set the constant K equal to M-1, where M is the order of the harmonic desired.

The IBM input card is divided into two fields and the appropriate values for M and K are entered with the following layout (place all numbers to the extreme right of each field):

Columns	1-5	6-10
Constant	M	K
IBM Card	---xx	---xx

*The Fortran program allows storage for 50 orders (p) but only the first 44 are significant since the maximum number n of readings is 90, and the condition $n > 2p$ must be satisfied.

The output is printed on-line, where J is the order of the harmonic. The value of A is printed separately, followed by one line for the coefficients B, C, Δ, and β for each harmonic. The letter symbols A, J, B, C, DELTA, and BETA are also printed.

A = ± 0.xxxx

J = xx   B = ±0.xxxx   C = ± 0.xxxx   DELTA = ± 0.xxxx   BETA = xxx.xxx

The coefficients A, B, C, and Δ are less than one degree, due to the type of mechanical errors involved. If the values are negative a negative sign will be printed. β may be an angle from -90 to 270 degrees.

PROGRAM 8705

On the first card to be entered, following the program deck, values for three constants must be specified. The values depend on the experimental conditions. The constants are:

N   The number of readings taken through the rotation. Maximum of 90 readings allowed.

M   The number of orders that are to be determined. The number of orders that can be determined is limited according to the form N = 2M + 1. Therefore with the above condition of 90 readings, solutions can be found for 44 orders.

CONV The conversion factor determined as follows:

The conversion factor depends on the units in which the data is obtained. Only four significant digits of the data are retained. The following table indicates the derivation of CONV for three types of reading instruments. The multiplication factor will be explained below.

Reading Instr.	Units	Multi. Factors	Conversion Factor	CONV
Iconolog	Degrees (.0xxxx)	10^5	1×10^{-5}	1.0E-05
Auto-collimator	Seconds (xxx.x)	10^1	$1/3600 \times 10^{-1}$	2.7777777E-05
SAMI	Inches (.xxxx)	10^4	$\frac{5.023}{3600} \times 10^{-1}$	1.3952777E-04

The IBM input card is divided into three fields and the appropriate values for N, M, and CONV are entered with the following layout (place all numbers to the extreme right of each field):

Columns	1-5	6-10	11-24
Constant	N	M	CONV
IBM Card	---xx	---xx	_x.xxxxxxxE-0X

Use of the correct conversion factor changes all input data to degrees, and the coefficients will also print on-line in degrees.

The next set of cards contains the readings R_k. These readings must be adjusted by the multiplication factors listed in the above table, so that all R_k enter the IBM in the same form. The data is placed on the cards in the same order as it was recorded. The IBM input cards are divided into 14 fields and the data is entered into the cards with the following layout (place all numbers to the extreme right of each field, and if there are more than 14 numbers to be entered, all 14 fields must be used before the next card is punched):

Columns	1-5	6-10	----------------65-70
Data R_k	±xxxx	±xxxx	----------------±xxxx

The next set of cards contains the readings θ_k in degrees to four decimal places. The data is placed on the cards in the same order as it was recorded and corresponding to the R_k data. The flexibility of this program is enhanced by the fact that the θ_k readings can be of uneven increments and they do not need to cover a full 360-degree rotation. The input cards are divided into eight fields and the data is entered into the cards with the following layout:

Columns	1-9	10-18	----------	64-72
Data θ_k	xxx.xxxx	xxx.xxxx	----------	xxx.xxxx

The output is printed on-line for the values of J, A, B, C, Δ, and β where J indicates the order of the harmonic coefficients. The letter symbols J, A, B, C, DELTA and BETA are also printed.

J = xx,   A = ± 0.xxx,   B = ± 0.xxxx,   C = ± 0.xxxx,

DELTA = = 0.xxxx, BETA = xxx.xxx. A new set of data cards, placed behind the preceding set, may now be read in.

The coefficients of A, B, C, and Δ are less than one degree due to the type of mechanical errors involved. If the values are negative, a negative sign will be printed. β may be an angle from -90 to 270 degrees. The values of A for orders higher than the first will be zero.

Appendix D

CALIBRATION REPORT

This appendix is an example of a previously distributed calibration report. It is included here as a reference. Each calibration was preceded by a cover sheet. For that data described by a sine-cosine curve, a graph of the measurements was included.

CINETHEODOLITE CALIBRATION DATA, AZIMUTH
MISLEVEL AND ROLLERPATH ERROR

1. The constants are computed by NOTS IBM Program 8702. They are:

J	=	the order of the sine-cosine curve
DELTA	=	the amplitude of the sine-cosine curve
BETA	=	the phase angle of the sine-cosine curve specifying the azimuth dial reading for which $\Delta_J \cos(J\theta - \beta_J) = M_J(\theta)$, θ_o will be taken as zero on the dial.

2. The first order sine-cosine curve ($J = 1$) is the computed mislevel. This mislevel value may be taken as a good estimate of mislevel when the instrument has been leveled to within one-fourth of a division on the level vials. (Standard procedure is to level to within one-fourth of a division of the vial 10 minutes prior to event time.) The data does not include dynamic shifts of the levelness.

3. For values of ($J > 1$), Delta and Beta give harmonic constants of a component of the bearing wobble.

4. The component of wobble parallel to the optic axis is added to the elevation angle.

5. The component of wobble parallel to the elevation axis is added to the standards error.

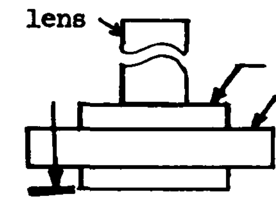
6. A component of wobble error, as a function of the azimuth dial angle θ, is

$$\sum_J \Delta_J \cos(J\theta - \beta_J)$$

AZIMUTH MISLEVEL AND ROLLER PATH - CALIBRATION DATA SHEET No. 1
IIND NOTS 4120/5 (9-61)

CAMERA NO. 2 MK. 2		CALIBRATED AT IOB	EQUIPMENT ALIGNMENT
CAMERA CODE NO. 2	CAMERA LOC IOB	REMARKS	
DATE 10 SEPT. 60			
CREW MACE			
JOSEPHSON			

EQUIPMENT ALIGNMENT

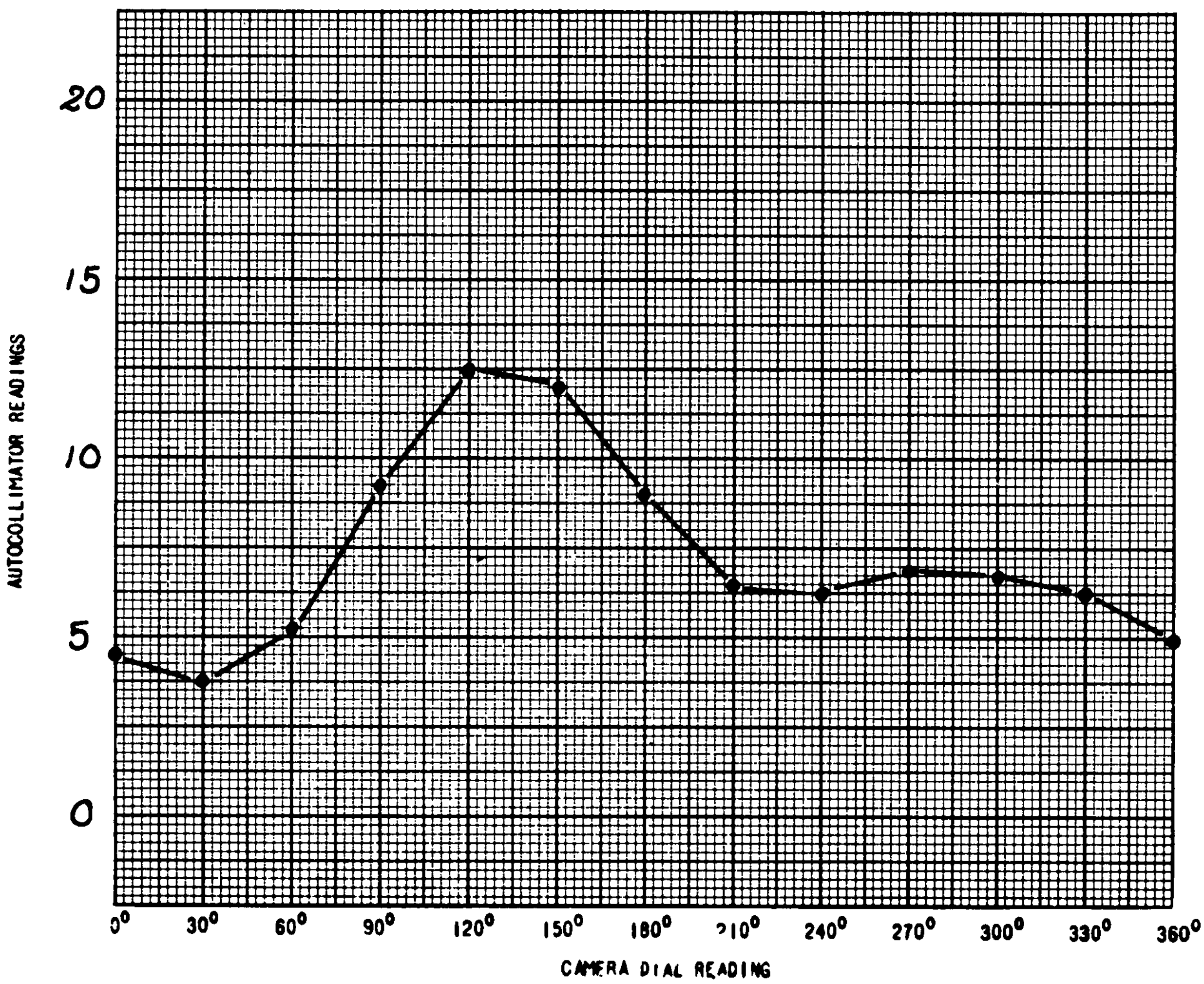


DRAW IN ARROW FOR THE AUTOCOLLIMATOR AND LOCATE THE "FARRAND" MIRROR.

MEASUREMENTS

DEGREES	AZIMUTH DIAL θ_A	AUTOCOLLIMATOR READINGS FORWARD	BACK	FORWARD			AVERAGE
0	SAME	5.4	4.5	4.0			4.6
30		4.1	3.8	3.4			3.8
60		5.2	5.5	4.8			5.2
90		9.6	8.5	9.4			9.2
120		12.5	12.3	12.5			12.4
150		11.6	12.0	12.4			12.0
180		8.6	9.5	8.8			9.0
210		6.1	6.9	6.4			6.5
240		6.5	6.4	6.0			6.3
270		7.1	7.0	6.5			6.9
300		6.6	7.0	6.5			6.7
330		6.3	6.5	6.0			6.3
360		5.1	5.0	4.7			4.9

AZIMUTH MISLEVEL AND ROLLER PATH ERROR - ⊥ TO ELEV. AXIS	AZIMUTH MISLEVEL AND ROLLER PATH ERROR - ‖ TO ELEV. AXIS	CAMERA NO. 2 Mk 2
AZIMUTH DIAL ECCENTRICITY	(CIRCLE APPROPRIATE TITLE)	CAMERA CODE 2
ELEVATION DIAL ECCENTRICITY		DATE 10 Sept. 60

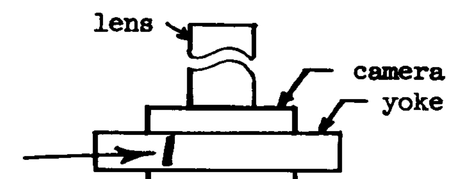


EDPM COMPUTED CONSTANTS				
j	B_j	C_j	Δ_j	β_j
1	-.0007	.0004	.0008	152.337
2	-.0002	-.0006	.0006	256.273
3	.0001	.0000	.0001	15.069

NAVORD NOTS 4120/10 (10/61)

AZIMUTH MISLEVEL AND ROLLER PATH - CALIBRATION DATA SHEET No. 1
11ND NOTS 4120/5 (9-61)

CAMERA NO. 2 MK. 2		CALIBRATED AT 10B	EQUIPMENT ALIGNMENT
CAMERA CODE NO. 2	CAMERA LOC 10B	REMARKS	
DATE 15 SEPT. 60			
CREW MACE			
BIL			

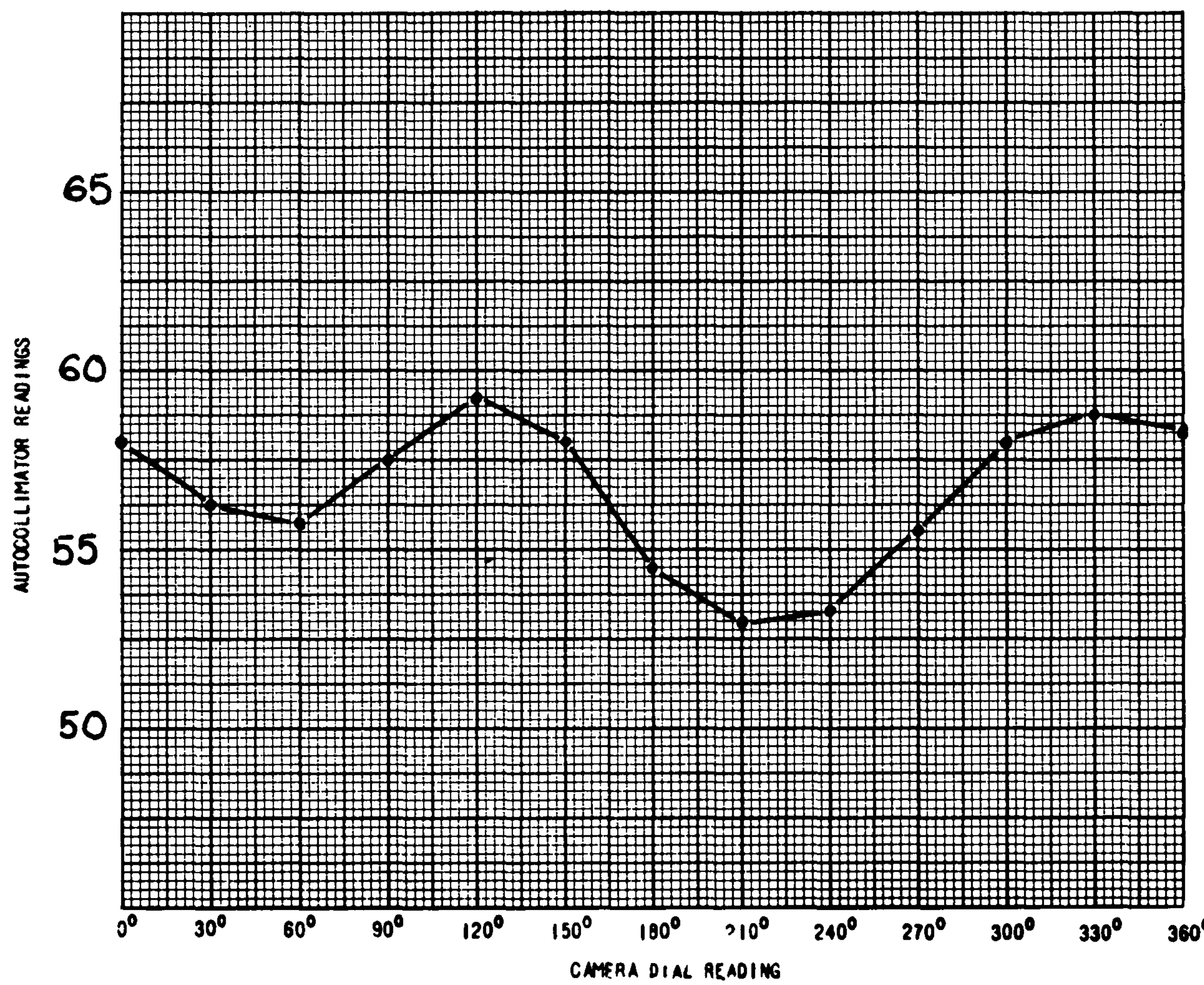


DRAW IN ARROW FOR THE AUTOCOLLIMATOR AND LOCATE THE "FARRAND" MIRROR.

MEASUREMENTS

DEGREES	AZIMUTH DIAL θ_A	AUTOCOLLIMATOR READINGS FORWARD	BACK	FORWARD			AVERAGE
0	SAME	58.3	58.1	57.5			58.0
30		56.4	56.3	56.3			56.3
60		55.8	55.8	55.7			55.8
90		57.5	57.3	57.8			57.5
120		59.8	58.7	59.0			59.2
150		58.2	57.6	57.8			57.9
180		54.5	54.5	54.4			54.5
210		52.6	53.0	53.2			52.9
240		52.9	53.4	53.6			53.3
270		55.5	54.9	56.1			55.5
300		57.8	57.6	56.7			57.4
330		59.3	58.7	58.4			58.8
360		58.3	58.1	58.6			58.3

AZIMUTH MISLEVEL AND ROLLER PATH ERROR - ⊥ TO ELEV. AXIS	AZIMUTH MISLEVEL AND ROLLER PATH ERROR - ‖ TO ELEV. AXIS	CAMERA NO. 2
AZIMUTH DIAL ECCENTRICITY	(CIRCLE APPROPRIATE TITLE)	CAMERA CODE 2
ELEVATION DIAL ECCENTRICITY		DATE 15 Sept. 60



EDPM COMPUTED CONSTANTS				
j	B_j	C_j	Δ_j	β_j
1	.0004	.0003	.0005	42.638
2	.0000	−.0006	.0006	268.236
3	.0001	.0000	.0001	10.125

TIND NOTS 4120/10 (10/61)

CINETHEODOLITE CALIBRATION DATA,
DIAL ECCENTRICITY

1. The constants given for azimuth dial eccentricity are computed by NOTS IBM Program 8702 per Technical Note No. 3063-71.

2. The constants given for elevation dial eccentricity are computed by NOTS IBM Program 8705 per Technical Note No. 3063-75.

3. The computed constants are J, Delta, and Beta where:

J	=	the order of the sine-cosine curve
DELTA	=	the amplitude of the sine-cosine curve
BETA	=	the phase angle of the sine-cosine curve specifying the dial reading where $\Delta_J(\cos(J\theta - \beta_J) = e_J(\theta)$, θ_o will be taken as zero on the dial.

4. The eccentricity error, as a function of θ, is

$$\sum_J \Delta_J \cos(J\theta - \beta_J).$$

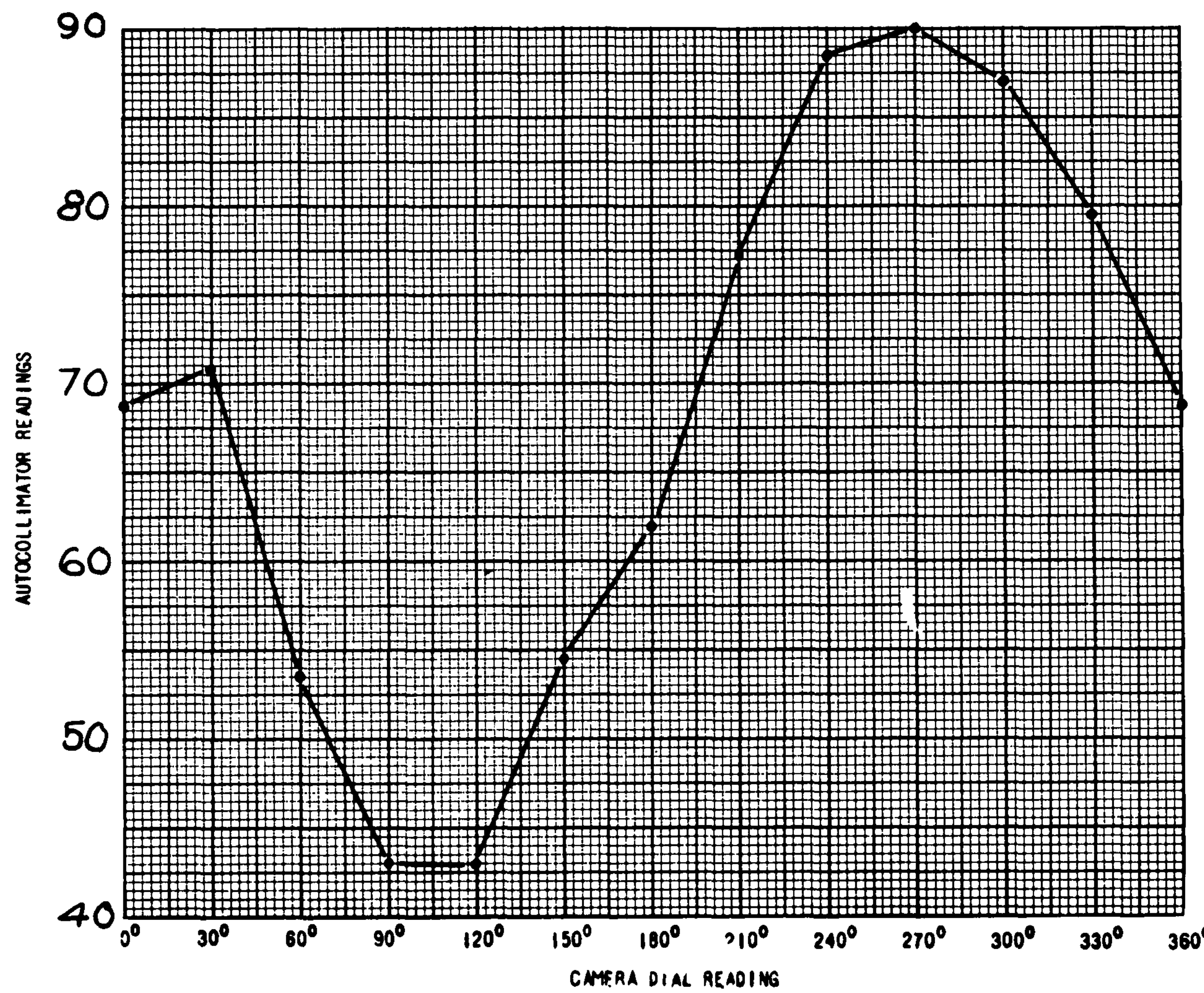
AZIMUTH ECCENTRICITY - CALIBRATION DATA SHEET NO. 2
LIND NOTS 4120/6 (9-61)

CAMERA NO. 2 Mk. 2	POLYGON NO. 93867 / 1ST FACE 240° / 2ND FACE 270°	NOTE: REPEAT MEASUREMENTS IF CLOSURE OF READINGS DOES NOT OCCUR. CHECK FOR LOOSE CLAMPS. READINGS ACROSS THE PAGE SHOULD BE WITHIN A TEN-SECOND RANGE.
CAMERA CODE 2 / CAMERA LOC IOB	REMARKS	
DATE 16 SEPT. 60		
CREW MACE		
JOSEPHSON		* POLYGON CORRECTIONS ARE FOUND IN T.N. 3063-102

MEASUREMENTS

DEGREES	AZIMUTH DIAL θ_A	AUTOCOLLIMATOR READINGS FORWARD	BACK	FORWARD			AVERAGE	POLY.* CORR.	CORRECTED READINGS
0	SAME	7'10.7"	7'16.2"	7'14.1"			13.7	-5.0	68.7
30	↓	7'7.7"	7'6.8"	7'7.0"			7.2	3.5	70.7
60		6'51.5"	6'51.0"	6'54.5"			52.3	1.2	53.5
90		6'45.5"	6'42.3"	6'39.4"			42.4	.7	43.1
120		6'43.7"	6'42.7"	6'44.7"			43.7	-.6	43.1
150		6'50.5"	6'47.7"	6'52.9"			50.4	4.0	54.4
180		7'3.0"	7'06.3"	7' .4"			3.2	-1.1	62.1
210		7'19.8"	7'20.2"	7'22.0"			20.7	-3.4	77.3
240		7'23.6"	7'22.2"	7'25.1"			23.6	4.8	88.4
270		7'32.3"	7'30.7"	7'31.4"			31.5	-1.6	89.9
300		7'28.7"	7'27.7"	7'29.5"			28.6	-1.5	87.1
330		7'19.6"	7'21.5"	7'19.7"			20.3	-.9	79.4
360	↓	7'14.5"	7'14.2"	7'12.7"			13.8	-5.0	68.8

AZIMUTH MISLEVEL AND ROLLER PATH ERROR - ⊥ TO ELEV. AXIS	AZIMUTH MISLEVEL AND ROLLER PATH ERROR - ‖ TO ELEV. AXIS	CAMERA NO. 2
AZIMUTH DIAL ECCENTRICITY	(CIRCLE APPROPRIATE TITLE)	CAMERA CODE 2
ELEVATION DIAL ECCENTRICITY		DATE 16 Sept. 60



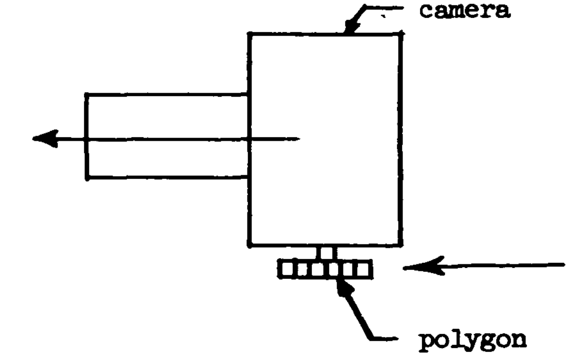
EDPM COMPUTED CONSTANTS

j	B_j	C_j	Δ_j	β_j
1	.0013	−.0061	.0062	281.730
2	.0001	.0010	.0010	83.010
3	−.0001	.0007	.0007	98.973

IIND NOTS 4120/10 (10/61)

ELEVATION DIAL ECCENTRICITY - CALIBRATION DATA SHEET NO. 3
IIND NOTS 4120/7 (9-61)

CAMERA NO. 2 MK. 2	REMARKS	EQUIPMENT ALIGNMENT
CAMERA CODE 2 — CAMERA LOC 10B		
DATE 16 SEPT. 60		
CREW MACE		
JOSEPHSON		
POLYGON NO. 81547		
1ST FACE 0° — 2ND FACE 345°		DRAW IN ARROW FOR AUTOCOLLIMATOR.

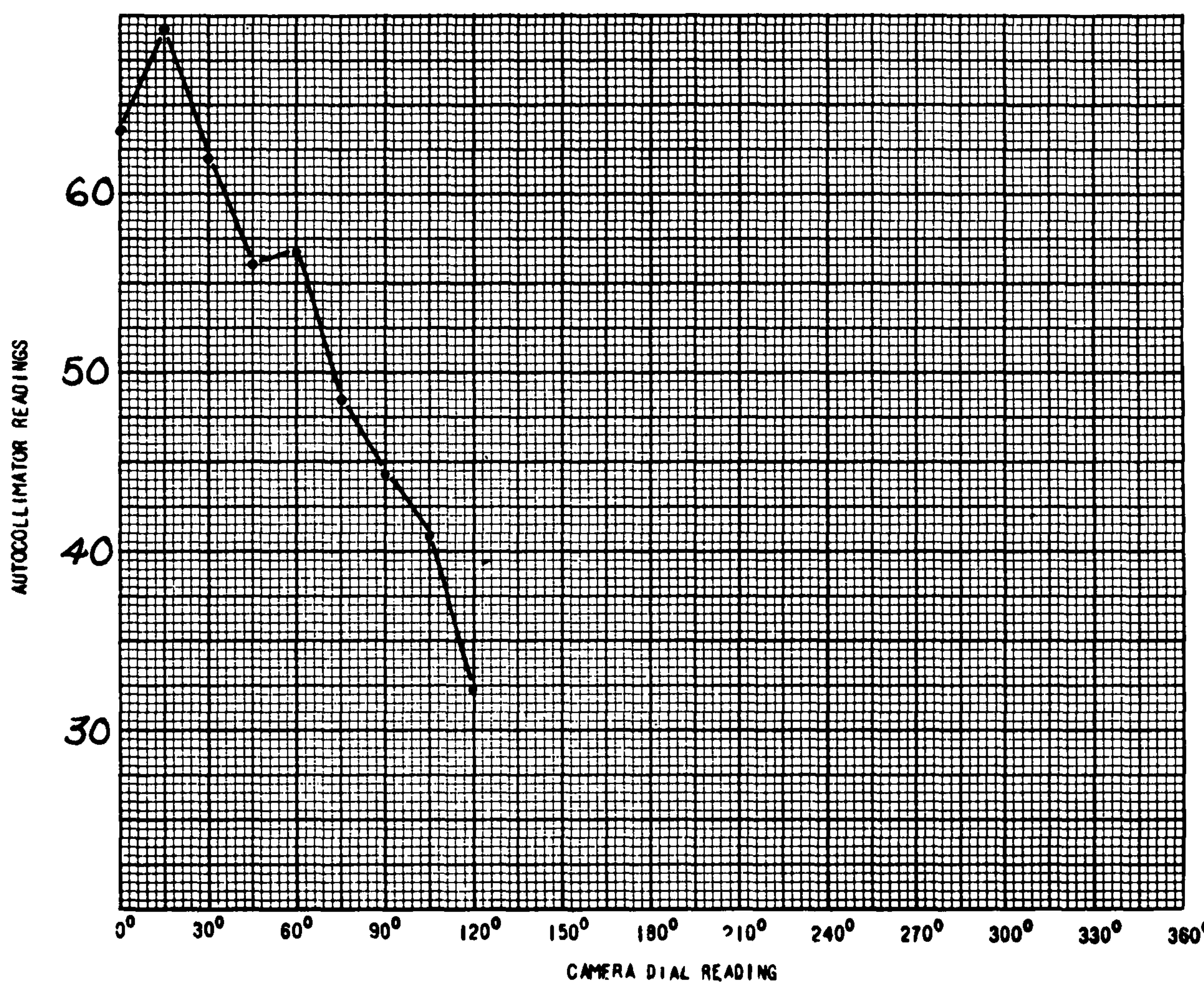


MEASUREMENTS

DEGREES	ELEVATION DIAL ϕ_E	AUTOCOLLIMATOR READINGS UP	DOWN	UP			AVERAGE	POLY. CORR.	CORRECTED READINGS
0	SAME	6'5.7"	6'4.0"	6' 5.5"			5.1	-1.5	6.3.6
15		6'3.4"	6'9.5"	6'6.8"			6.6	2.7	6.9.3
30		6'1.3"	6' .6"	6'2.5"			1.5	.5	6.2.0
45		5'54.5"	5'59.7"	5'58.6"			57.6	-1.4	5.6.2
60		5'54.9"	5'49.9"	5'56.8"			55.5	1.3	5.6.8
75		5'48.7"	5'48.9"	5'47.4"			48.3	-.3	4.8.0
90		5'45.0"	5'45.2"	5'41.2"			43.8	.5	4.4.3
105		5'45.6"	5'40.6"	5'39.5"			41.9	-1.0	4.0.9
120		5'35.0"	5'34.1"	5'28.2"			32.4	-.1	3.2.3

NOTE: READINGS ACROSS THE PAGE SHOULD BE WITHIN A TEN-SECOND RANGE.

AZIMUTH MISLEVEL AND ROLLER PATH ERROR - ⊥ TO ELEV. AXIS	AZIMUTH MISLEVEL AND ROLLER PATH ERROR - ∥ TO ELEV. AXIS	CAMERA NO. 2
AZIMUTH DIAL ECCENTRICITY	(CIRCLE APPROPRIATE TITLE)	CAMERA CODE 2
ELEVATION DIAL ECCENTRICITY		DATE 16 Sept. 60



EDPM COMPUTED CONSTANTS

j	B_j	C_j	Δ_j	β_j
1	.0059	-.0001	.0059	-1.060
2	.0000	-.0001	.0001	-61.021
3	.0001	.0000	.0001	-12.197

11ND NOTS 4120/10 (10/61)

CINETHEODOLITE CALIBRATION DATA,
LENS TUBE SAG DUE TO GRAVITY

1. The measurements have been made according to T.N. 3063-104.

2. The values given are the deflections due to gravity of the optic axis in both the forward and dumped positions.

3. The resulting values are accurate to ±3 seconds of arc.

4. $S_F \cos E$ is the angle to be added algebraically to the elevation dial reading where $E \leq 90°$.

5. σ_s is the vertical correction to be added to the elevation dial reading.

LENS TUBE SAG DUE TO GRAVITY - CALIBRATION DATA SHEET No. 4

LIND NOTS 4120/8 (9-61)

CAMERA NO. 2 Mk. 2		MEASUREMENTS				
		AUTOCOLLIMATOR READINGS				
CAMERA CODE 2	CAMERA LOCATION 10B	FORWARD = F	DUMPED = D	s_f	s_d	$s_f + s_d$
DATE 17 SEPT. 60		5'31.6"	4 38.2	31.6	-21.8	9.8
LENS NO. B35646	LENS CODE 2004	5 30.7	4 38.2	30.7	-21.8	8.9
CREW MACE		5 31.8	4 39.5	31.8	-20.5	11.3
OSTRANDER						
REMARKS						3|30.0
		$s_f = F - 5' 0''$	$s_d = D - 5' 0''$		AVERAGE $(s_f + s_d)$ =	10.0

WT kg	AUTOCOLLIMATOR READINGS FORWARD	DUMPED	RATIOS
1	F_1 = 5 32.2	D_1 = 5 28.1	
2	F_2 = 5 53.4	D_2 = 46.3	$R = (F_2 - F_1)/(D_2 - D_1)$ = 21.2 / 18.2 = 1.16
3	F_3 = 6 17.1	D_3 = 6 8.7	$R = (F_3 - F_1)/(D_3 - D_1)$ = 44.9 / 40.6 = 1.11
4	F_4 = 6 36.4	D_4 = 6 29.4	$R = (F_4 - F_1)/(D_4 - D_1)$ = 64.2 / 61.3 = 1.05
			AVERAGE R =

CALCULATIONS

SAG IN FORWARD POSITION = S_F $\quad S_F = -S_F' = -\dfrac{2R\,(s_d + s_f)}{(R+1)} =$ -10.5 SEC. = -.175 DEG.

SAG IN DUMPED POSITION = S_D $\quad S_D = S_D' = \dfrac{2\,(s_d + s_f)}{(R+1)} =$ 9.5 SEC. = .158 DEG.

$S_F = -RS_D$

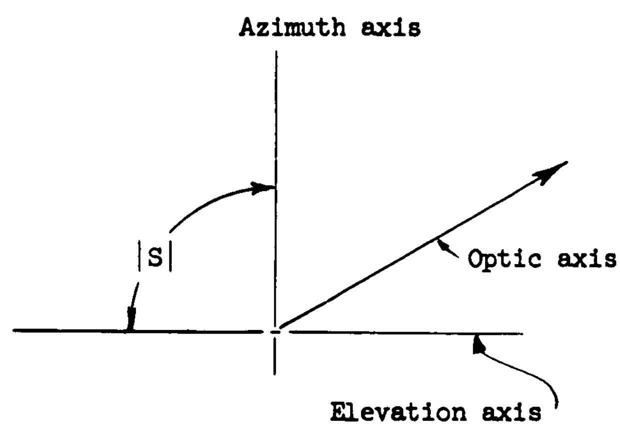
$$\phi_s = \frac{S_D + S_F}{2} = -.0083 \text{ DEG.}$$

CINETHEODOLITE CALIBRATION DATA
STANDARDS ERROR

1. Standards error has been measured according to Technical Note 3063-96.

2. The value given is |S| in degrees. This is the angle between the azimuth and elevation axis. If the observer faces in the direction the optic axis points, |S| measures the angle to the arm of the elevation axis extending to the observer's left; i.e., in the direction of the tracking scope. See sketch, below.

3. The standards error s defined in T.N. 303-1 is given by the relationship $s = 90 - |s|$.



STANDARDS ERROR - CALIBRATION DATA SHEET No. 5
IIND NOTS 4120/9 (9-61)

CAMERA NO. 2 MK. 2		REMARKS
CAMERA CODE 2	CAMERA LOCATION 10B	
DATE 17 SEPT. 60		
CREW MACE		
JOSEPHSON		

MEASUREMENTS			CALCULATIONS
1. CAMERA IN FORWARD POSITION:	a_0 = 270	DEG.	1. CALCULATE THE FOLLOWING VALUES:
BUBBLE READINGS:	A_0 = 8.4		A) $\gamma_1 = A_2 + A_1 - 2A_0$ = −1.0
	B_0 = 5.8		B) $\gamma_2 = B_2 + B_1 - 2B_0$ = −1.0
	A = 8.4	= A_1	C) $\gamma_3 = A_4 + A_3 - 2A_0$ = −2.5
	B = 6.6	= B_1	D) $\gamma_4 = B_4 + B_3 - 2B_0$ = −2.5
2. CAMERA IN DUMPED POSITION:	a_0 = SAME		E) $s = \frac{10.5\,(\gamma_1 + \gamma_2 + \gamma_3 + \gamma_4)}{8}$ = −9.2 SEC.#
BUBBLE READINGS:	A' = 7.4	= A_2	
	B' = 5.0	= B_2	F) s/3600 = −.0026 DEGREES
3. CAMERA IN DUMPED POSITION:	$a_0 + 180^0$ = 90	DEG.	2. *IF s IS NEGATIVE $\lvert S \rvert = 90 + s$ = 90.0026 DEG. } CHOOSE ONE
BUBBLE READINGS:	A' = 6.5	= A_3	IF s IS POSITIVE $\lvert S \rvert = 90 - s$ = DEG. }
	B' = 4.1	= B_3	
4. CAMERA IN FORWARD POSITION:	$a_0 + 180^0$ = SAME		
BUBBLE READINGS:	A = 7.8	= A_4	#10.5 IS A CALIBRATION CONSTANT OF THE REVERSION VIAL USED AT NOTS.
	B = 5.2	= B_4	*THE HIGH STANDARD IS IN THE SAME DIRECTION AS THE BUBBLE DRIFT WHEN CHANGING THE BUBBLE SETTING FROM A_0 TO A_1.

Appendix E

STANDARDS ERROR REFERENCE

The derivation of the equations of γ_i to compute the standards error using a level vial follows. This method eliminates the effects of azimuth mislevel. Reference to Fig. 15 will aid the discussion.

At an arbitrary azimuth dial reading a_o (external azimuth scale) the readings on the "A" scale are A_o and A_1 in the forward position, and A_2 in the dumped position. The cinetheodolite is then rotated 180 degrees in azimuth to $a_o + 180$ where A_3 is read in the dumped position and A_4 in the forward position.

At azimuth a_o:

$$s - m = \frac{A_2 - A_1}{2} + (A_1 - A_o), \text{ or}$$

$$2(s - m) = A_2 + A_1 - 2A_o = \gamma_1$$

At azimuth $(a_o + 180)$:

$$s + m = \frac{(A_3 - A_4)}{2} + (A_4 - A_o), \text{ or}$$

$$2(s + m) = A_4 + A_3 - 2A_o = \gamma_3$$

Similar reasoning gives:

$$2(s - m) = B_2 + B_1 - 2B_o = \gamma_2$$

$$2(s + m) = B_4 + B_3 - 2B_o = \gamma_4$$

Adding the four equations for γ_i, i = 1, 2, 3, 4 yields:

$$s = 1/8 \sum_{i=1}^{4} \gamma_i$$

Each bubble division is equivalent to 10.5 seconds of arc on the average. Therefore,

$$s = \frac{10.5}{8} \sum_{i=1}^{4} \gamma_i \text{ seconds of arc.}$$

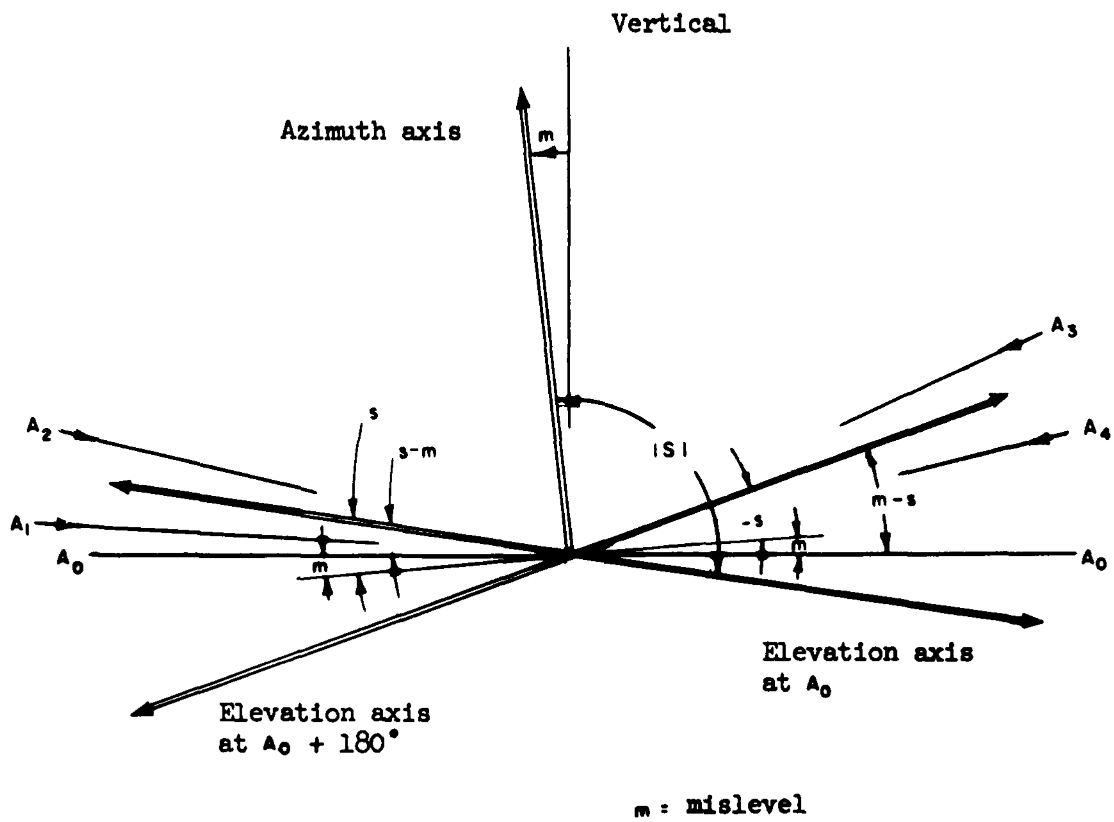


FIG. 15. Standards Error.

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